

**INDUCTIVELY COUPLED PLASMA
DRY ETCHING PROCESS ON
PLANAR LIGHTWAVE CIRCUIT FABRICATION**

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DRY ETCHING PROCESS ON
PLANAR LIGHTWAVE CIRCUIT FABRICATION**

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ORIGINAL LITERARY WORK DECLARATION

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ABSTRACT

The main objective of this project is to master state-of-the-art techniques and knowledge in silica etching in order to achieve high quality waveguide circuit on Planar Lightwave Circuit devices. Another objective is to optimize the clean room research strength, surface characterization, microscopy techniques and similar semiconductor manufacturing processes.

Initially, these processes were conducted with wet etching method that utilized diluted hydrofluoric acid (HF) and buffered oxide etch (BOE). Several problems arising such as mask peel-off, poor sidewall profile and defect waveguide channel during the pattern transfer process due to its' isotropic nature.

Alternatively, dry etching method was conducted via Inductively Coupled Plasma (ICP) etch system due to the failure of wet type silica etching process. For gases selection, a mixture of Tetrafluoromethane/Argon (CF_4/Ar), Tetrafluoromethane (CF_4) was compared with Hexafluoroethane (C_2F_6). C_2F_6 gas was found to be the most suitable etch gas for PLC silica etching by evaluating the good waveguide channel profile and selectivity. From the results obtained, the highest etch rate of about 226 nm/min was achieved at ICP power of 1000 W, Bias power of 60 W, process pressure and gas flow rate of 10 mTorr and 35 sccm, respectively. Otherwise, process condition of ICP silica etching at ICP power of 500 W, Bias power of 60 W, process pressure of 10 mTorr, gas flow rate of 35 sccm and etch duration of 30 minutes resulted in the highest selectivity of silica to chromium mask of about 63. For overall optimum process condition of ICP silica etching, etch rate of about 192 nm/min and selectivity of about 23 was obtained at ICP power of 900 W, Bias power of 60 W, process pressure and C_2F_6 flow rate of 10 mTorr and 40 sccm respectively for 30 minutes duration.

ABSTRAK

Objektif projek ini adalah menguasai teknik dan kemahiran dalam proses punaran Si untuk mencapai litaran pandu gelombang yang berkualiti tinggi dalam pembuatan alatan-alatan litar bersepadu optikal. Tambahan pula, projek ini mengembangkan kemahiran selanjutnya dan teknik berguna untuk peningkatan strategi dalam penyelidikan bilik bersih, ujikaji permukaan, teknik-teknik mikroskopi dan proses pembuatan semikonduktor yang serupa. Ujikaji dan analisa tentang proses perpindahan corak-corak kaca adalah dikaji serentakannya. Pada awalnya, proses perpindahan corak kaca dijalankan dalam cara basah dengan mengguna asid hidrofluorik dan “BOE”. Beberapa masalah ditimbulkan seperti keguguran topi logam, dinding tepi yang tidak memuaskan dan cacatan pada corak pandu gelombang atas sifat-sifatnya dalam cara basah. Proses perpindahan corak-corak kaca cara kering dijalankan dengan “Inductively Coupled Plasma (ICP) Etch System” selepas kegagalan cara basah. Eksperimen pertama, gas-gas “Tetrafluoromethane/Argon (CF_4/Ar)”, “Tetrafluoromethane (CF_4)” serta “Hexafluoroethane (C_2F_6)” dikaji dan diperbandingkan. Selepas kajian tersebut, gas “Hexafluoroethane (C_2F_6)” terpilih sebagai gas yang sesuai untuk projek ini. Selanjutnya, beberapa parameter dikaji untuk peningkatan proses perpindahan corak kaca. Beberapa lingkungan keadaan proses perpindahan corak kaca telah dihasilkan untuk keperluan tertentu. Kadar tertinggi perpindahan corak kaca sebanyak 226 nm/saat telah dicapai pada keadaan proses 1000 W kuasa “ICP”, 60 W kuasa pincang, 10 mTorr tekanan proses dan 35 sccm kadar pengaliran gas C_2F_6 . Selainnya, keadaan proses pada 500 W kuasa “ICP”, 60 W kuasa pincang, 10 mTorr tekanan proses dan 35 sccm kadar pengaliran C_2F_6 dalam masa 30 minit, menghasilkan kadar perpindahan corak tertinggi

pada nisbah kaca kepada topi kromium sebanyak 63. Pada keseluruhannya, keadaan perpindahan corak kaca terbaik dari segi keseluruhan adalah kadar perpindahan corak kaca sebanyak 192 nm/minit dan nisbah kadar perpindahan corak kaca kepada topi kromium sebanyak 23 yang dihasilkan pada 900 W kuasa “ICP”, 60 W kuasa pincang, 10 mTorr tekanan proses dan 40 sccm kadar pengaliran gas C_2F_6 .

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CHAPTER 1

INTRODUCTION

The emergence and progress in photonics technology has had a dramatic impact in today's telecommunication as well as in the information science and engineering. For example, optical fibres have already taken over many previous functions of electronic systems [1]. Recent advances in the development of low-loss optical planar waveguide devices have revolutionized the field of telecommunications. Further the advent of laser, which is a coherent source of light and a suitable carrier wave is capable of carrying enormously large amount of information compared to those of radio waves and microwaves.

Typically, a light wave communications system consists of a transmitter (usually a semiconductor laser diode which emits in the infrared (IR) region) that is associated with electronics for modulating signals; a transmission medium (optical fibre) to carry the modulated light beam; and a receiver consisting of an optical detector and associated electronics for retrieving and demodulating the signal.

The transmitted data capacity in optical communication systems has grown tremendously in the past years to fulfill the needs of the rapidly expanding telecommunication market, where the transport of data is substantially exceeds the aggregate data rate of telephone and voice.

Time-division-multiplexed systems have increased from 622 Mb/s to 2.5 Gb/s and 10 Gb/s, even the wide deployment of 40-Gb/s systems is within the reach for network backbones. Furthermore, wavelength-division multiplexing (WDM) with large channel counts offer extensions of capacity in existing fibre systems [2]. WDM transmission systems are widely deployed in wide-area networks (WANs), and are now beginning to enter metropolitan area network (MAN) and customer-premise network areas [3, 4].

Most of the optical links are still point-to-point in terms of configuration with the occasional optical WDM add/drop functions. However more advanced ring structures that also employ optical WDM add/drop functions are beginning to appear. In the future, fully meshed, optically transparent networks will be required with high-complexity optical-cross-connect features [5].

This evolution is driven by the requirements for flexibility in photonics network nodes particularly for optical transparency because the majority of the traffic in a node is pass-through [6]. The term *optical transparency* denotes the state in which data streams are kept in the photonic domain and redirected through optical switches. Electrical termination of all channels at each node is simply too inefficient and requiring a receiver/transmitter pair for each WDM channel.

1.1 Background

Optical fibres consist of a core region of transparent material that has higher refractive index and are surrounded by a cladding layer with a relatively lower refractive index. Optical fibres confine and guide light by applying the phenomenon of total internal reflection. One of the key elements that influence the vast improvement in fibre optics transmission is the tremendous reduction in the propagation loss of the glass. This was achieved in 1970s, especially by Corning Glass Works which produced a low loss fibre with 20dB/km propagation loss when implementing a He-Ne Laser wavelength at 632.8 nm [7]. The fibre type that is widely used today is the single mode fibres with a core diameter of about $9\mu\text{m}$ and the cladding diameter of about $125\mu\text{m}$. Optical fibres with the typical loss of 0.2dB/km at 1550nm wavelength and capable of transmission speeds between 2-10 Gbit/s are now commercially available [8].

Development in fibre optics communication networks has brought out huge demands on the passive optical components such as splitter, coupler, wavelength division multiplexers (WDM), isolators, circulators, and other components. High bit rate transmission systems may use WDM's to combine several wavelengths into a single fibre. Long span systems that use erbium doped fibre amplifier (EDFA) require a combination of tappers, filters and WDM's for pumping and controlling of cascaded amplifiers. Although these components have been realized in both bulk optics and fused fibre design, for large input/output configuration, the end products tend to be bulky with

higher insertion loss. Recently, an alternative to optical fibre devices based on the planar waveguide technology has been developed.

1.2 Introduction and Theory of Waveguide

A waveguide is a medium that confines and guides a propagating electromagnetic wave. It is called as a dielectric waveguide if it consists of a dielectric material that is surrounded by another dielectric material such as air, glass, or plastic, with a lower refractive index. An example of a dielectric waveguide is an optical fibre. Paradoxically, a metallic waveguide filled with a dielectric material is not a dielectric waveguide. In integrated optical circuits, an optical waveguide may consist of a thin dielectric film that is designed to have a rectangular cross-section.

There are five classes of loss that limit waveguide performance such as alignment mismatches, diffraction across the channel, insertion or mode-matching losses, reflective losses, and propagation losses. Simultaneous embossing of the waveguide and separation of channels eliminate alignment losses such as those incurred when trying to incorporate external fibre optics. Diffraction losses depend upon the shape of the waveguide mode and the distances over which it must travel unguided. These are minimized by using the zero-order waveguide mode, which has a slowly varying transverse intensity. Insertion losses when coupling free space light occur when the shape of the focused laser beam does not match the zero-order mode of the waveguide. Full mode-matching requires beam-shaping optics, while approximate mode-matching can be achieved by an

appropriate choice of focusing lens. Reflective losses will occur with any optical scheme that involves refractive index boundaries, and are reduced by minimizing the number of interfaces through which the light needs to pass. Propagation losses are negligible when the refractive index of the waveguide core is larger than that of the cladding.

1.2.1 Planar Waveguide Technology

In silica-based planar waveguide technology, wave guiding depends on the difference refractive index between the waveguide region and the surrounding medium. The basic requirement of a waveguide is to guide light along the defined paths. It needs a region of material with higher refractive index than the material surrounding it. The light is confined and guided as in it is in the optical fiber. The waveguide consists of 3 parts such as core, buffer and substrate layers as illustrated in Figure 3.

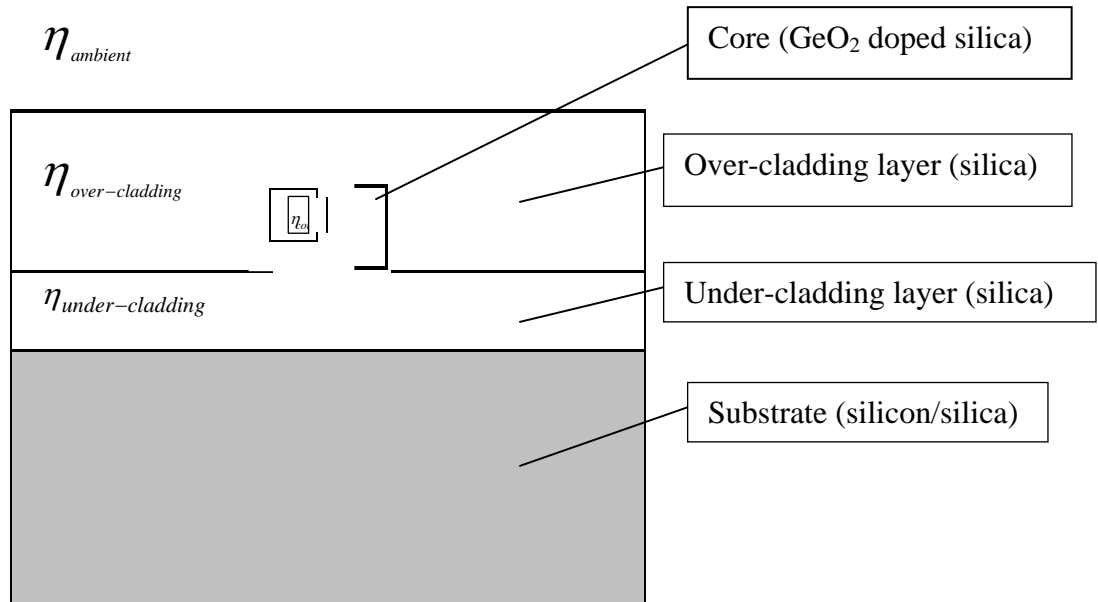


Figure 3: Cross-section of a single channel planar waveguide

The refractive index of the core exceeds that of the buffer and substrate layers. A light wave is trapped by total internal reflection and propagates within the high index region. This is fulfilled as long as refractive index of the core is greater than that of the under-cladding, and refractive index of the over-cladding is higher than that of the ambient. The under- and over-claddings that represent buffer layers have a similar refractive index as they are usually deposited by using the same transparent material. This mathematical relationship can then be deduced to be:-

$$\eta_{core} > \eta_{under-cladding}, \eta_{over-cladding} > \eta_{ambient} \quad (1.1)$$

$$\eta_{under-cladding} \cong \eta_{over-cladding} \quad (1.2)$$

Planar waveguide technology is based on creating optical waveguides on the substrates by using manufacturing processes that are similar to those of semiconductors. It is also known as planar lightwave circuit (PLC) where this technology can initially be used to create individual passive components namely Splitters and Arrayed-Waveguide Gratings (AWG). As processes for combining hybrid elements develop, it may be possible to have active devices such as Erbium Doped Waveguide Amplifiers (EDWA) and integrate it with other passive devices, on a single chip.

Silica-based optical waveguide have received much attention in recent years owing to the advantages of low cost, low propagation loss, hybrid optical packaging and good match to optical fibres [9]. Recent progress in planar waveguide development has

enabled complicated optical components to be fabricated within a 1cm x 1cm substrate wafer.

To address the limitation of the optical fibre components, integrated optical planar waveguides have been developed to meet the needs for low cost, high coupling efficiency and reliability. In this project, passive waveguides are studied in order to realise its fabrication for low-loss operation. The subjects of our interest are silica on silicon substrates namely splitters and AWG as depicted in figure 4 and 5.

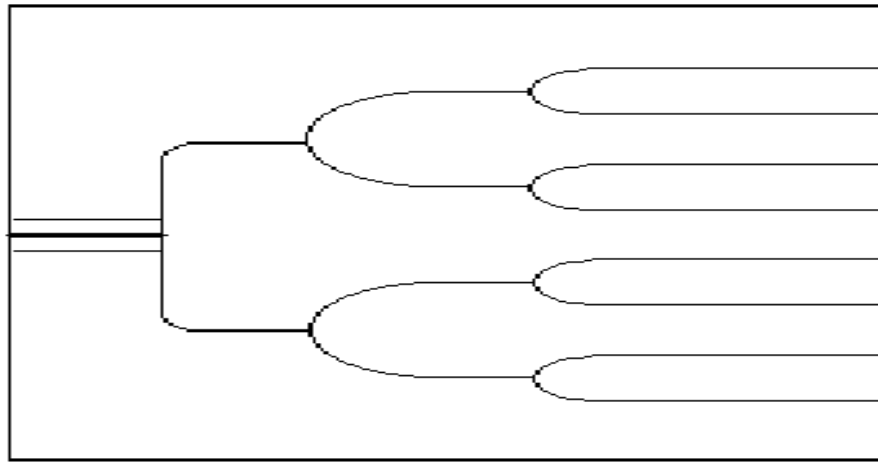


Figure 4: Schematic diagram of 1x8 Channel Planar Waveguide Splitter

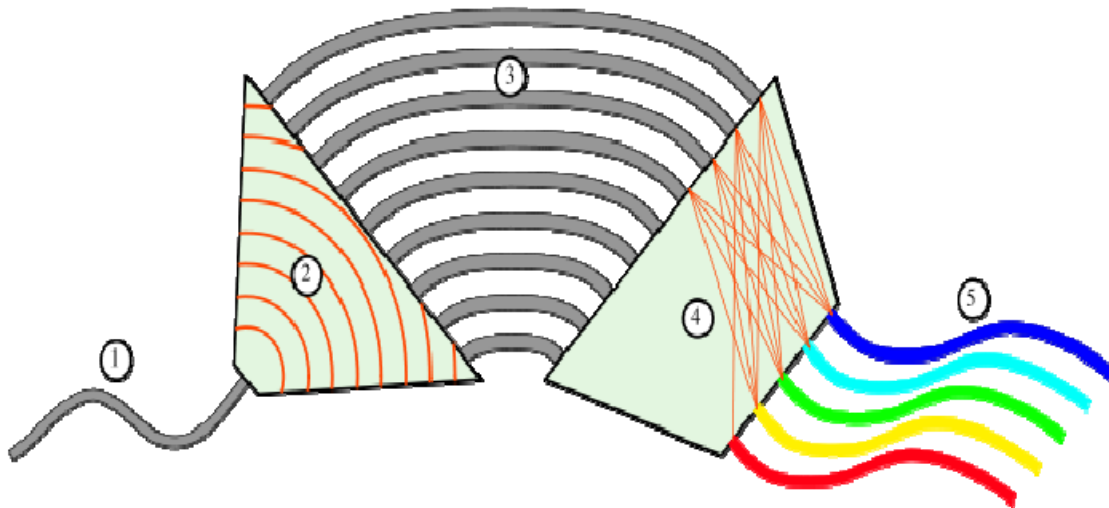


Figure 5: Schematic diagram of an Array Waveguide Grating (Wikipedia)

From figure 5, the incoming light (1) traverses into the demultiplex slab waveguide (2) and enters a bundle of optical fibres or channel waveguides (3). The fibres have different length and thus imply a different phase shift. At the exit of the fibres (3) the light propagates into the multiplex slab waveguide (4) and interferes at the entries of the output waveguides (5) in such a way that each output channel receives only light of a certain wavelength. The orange lines (figure 5) illustrate the light path and the light that travels from (1) to (5) is designated as a demultiplexer and from (5) to (1) is designated as a multiplexer.

As optical communication advances, more and more passive optical components are needed. For instance, broadband multiplexers are feasible for delivering voice and video to the home, combining pump and signal in an optical amplifier and adding a monitoring signal to the traffic in optical fibres. Dense wavelength division multiplexing (DWDM) systems need multiplexers and add-drop filters to combine and separate

channels of different wavelengths and to partially alter the traffic, respectively. In addition, other devices such as splitter and star couplers are used in broadcasting and low speed optical switches for sparing applications and network reconfiguration.

The demands for Internet access, telecoms and broadband services are the acknowledged forces that drive the global requirement for increasingly higher lightwave transmission capacity. DWDM has increased the amount of digital traffic that a fiber can carry by allowing more than one wavelength of light in the same fiber. It is established firmly as the technology for long-haul, large-capacity networks, and its use is now spreading throughout the metropolitan and access networks.

There are a variety of DWDM components that provide different functions within optoelectronic circuits. These are Multiplexers, Demultiplexers, Add/drop multiplexers, Filters, and Routers. The Multiplexers combine signals of different wavelengths before they all pass through a single optical fibre. The Demultiplexers or splitters separate signals of different wavelengths in order to emerge through different optical fibres. In addition, the Add/drop multiplexers have multiple functions to drop one or more wavelengths at a selected point and pick up other signals for transmission while transmitting other signals unchanged. For selective transmission and reflection of a particular wavelength, Filters can be included. In order, to direct certain wavelengths to different points in a circuit without separating all the signals in the fibre, routers can also be implemented.

Several approaches in designing DWDM components have been used. There are bulk devices, such as microelectromechanical systems (MEMS) and thin-film filters, fibre-type devices, such as fibre couplers, and planar devices, such as arrayed waveguide

gratings and variable optical attenuators. Planar integration has several advantages, including compactness, ease of fabrication and design advantages.

1.2.2 Silica-Based Planar Waveguide

Since silica is an inherently stable, with well controlled refractive index and low loss optical material, the silica-based waveguides are optically broadband and transparent, have high thermal and mechanical stability, polarization independent, and low loss fibre coupling (without taper). The central concept of a planar optical technology is to fabricate integrated devices within a block or slab of a transparent material. Channel waveguides can be configured to produce many useful integrated optical devices for communication signal processing.

Waveguide-class structures are becoming more popular with the expanding in photonics industry. Their complex functionality, parallel multi-channel operation and cost-effective planar fabrication have opened up many opportunities for systems designers that can lead to eventual integration into hybrid electro-optical microcircuits. Today's examples include silicon optical amplifiers (SOA), AWG and integrated optical circuits (IOC) where future uses will include on-board and even in-chip DWDM data buses. Owing to their fabrication techniques that involves semiconductor wafer processes, the materialisation of sophisticated parallel optical trains can be done cost-effectively.

1.3 Development of Photonics Technology

Photonics technology developed as an outgrowth of the first practical semiconductor light emitters invented in the early 1960s and optical fibers developed in the 1970s. In late 20th century, recent advancements in planar optics technology and waveguide-based photonic devices play important roles in modern communication systems and provided the infrastructure for the internet. These are specifically in the area of switches, power optical splitters/combiners, external modulator, wavelength-division multiplexers/demultiplexer and wavelength selective multiplexers, couplers, branching circuits and polarizer. The wide applications of these devices has led to immediate increases in production throughput, consistency and yield. Planar waveguides are considered as the basic structure of the more complex waveguides. Many of the optoelectronic devices designed in optical telecommunication networks are essentially passive optical waveguides that do not generate any light on their own but rather channel and guide the light into specific output ports.

One of the key manufacturing challenges is to design the silica core layer with an appropriate planar waveguide channel that requires clean, vertical and deep silica etching by Inductively Coupled Plasma etcher. The recent progress of integrated optical technologies from the research laboratory to the small scale commercialization has sped up the development of high etch rate and selective etching technology. As analogous to all optical media, the major challenge is to fabricate small sizes, low loss and high yield of PLC materials. Continuing progress in this area is essential to the successful deployment of these devices in real world instrumentation and systems [2]. It is generally

acknowledged that the only way to achieve lower costs and high yield is by implementing semiconductor manufacturing processes, packaging, design, and integration techniques. This leads the semiconductor manufacturing techniques that can define the waveguides, pits, grooves, and channels to be one of the main focuses in Planar Lightwave Circuit (PLC) development

1.4 Silica Waveguide Devices

The most prominent feature of silica waveguides is their simple and well-defined structure. This allows manufacturers to produce multi-beam or multistage interference devices such as arrayed-waveguide gratings (AWG) and lattice-form programmable dispersion equalizers. A variety of passive PLC's, such as NxN beam splitter, NxN star couplers, NxN AWG multiplexers, and thermo-optic matrix switches have been developed by employing silica-based optical waveguides. The substrates chosen are based on silicon or silica by implementing a combination of flame hydrolysis deposition (FHD) and reactive ion etching. Fine glass soot are produced via a quartz torch by oxy-hydrogen flame and deposited on the host substrate (Si or SiO₂). Once an under-cladding is deposited, the wafer is heated to high temperature for consolidation. Furthermore, the deposition and consolidation processes are repeated with a silica core layer. The circuit pattern is then fabricated by means of photolithography and reactive ion etching (RIE). Finally, core ridge structures are covered with an over-cladding layer before being consolidated again.

The rapidly growing optical communication market requires photonic components with ever-increasing functionality and complexity, that can be fabricated reliably at low cost. Of the various approaches used to fabricate photonic components, those based on planar waveguides technology have achieved high performance and represent a promising path toward compact integration of optical functions. Through its strong mode confinement, the approach makes it possible to integrate optical filter functions with higher functionality, as required for high-data-rate communication networks. The waveguide is based on the use of a germanium-doped silica core layer and silica buffer layers, and can be fabricated by using conventional chip fabrication techniques. Using the new approach, conventional passive optical components such as arrayed waveguide grating for DWDM transmission systems can be fabricated in a more compact way than using standard silica-on-silicon waveguide methods. Moreover, the realization of more enhanced, adaptive optical functions such as finite-impulse-response as well as infinite-impulse-response filters is possible. Reconfiguration is achieved through the thermo-optic effect.

Over the last decade the optical component industry and research community have embarked on a planar lightwave circuit (PLC) revolution. Recent breakthrough in photonics and microelectronics have driven this revolution, and by the commercial reality that new optical technologies must eventually be manufacturable and meet market requirements. The focus of photonics research and development has shifted away from the traditional source/fibre/detector based telecommunication links, to complex devices that incorporate microphotonic waveguides, high index contrast materials, photonic crystals, sub-wavelength diffractive structures, and highly integrated planar lightwave

circuits. Applications of planar lightwave circuits now encompass biomedical research, optical interconnects, transportation, environmental monitoring, and sensors for defence and security.

1.5 Basic Fabrication Process

The fabrication process includes wafer cleaning and handling, silica deposition, soot consolidation, chromium metal masking, photolithography, wet and dry etching. The instrumentation consists of FHD, ICP system, Direct Current (DC) magnetron sputter system, mask aligner system, spin coater, hot plate, oven, furnace, fume hood and wet bench. Additionally, the measurement and analysis equipment such as surface profiler, microscope, prism coupler, scanning electron microscopy (SEM), electron diffraction x-ray (EDX) and atomic force microscope (AFM) are also involved.

The fabrication of PLC is analogous to that of integrated circuit (IC) by utilising semiconductor technology which is based on four basic micro-fabrication techniques such as deposition, doping, patterning and etching. These four techniques are revolutionized and combined to build up the PLC from layer to layer. This process begins with a thin film that consists of silica film buffer layer which is deposited on the silicon wafer substrate. Then, the following doped silica core layer is deposited upon the under-cladding layer which behaves as the buffer layer. A chromium is then coated as mask layer by DC Sputter system, followed by a thin layer of light-sensitive chemical called photoresist that is coated on top of the chromium layer and written by employing

photolithography. The pattern is then transferred from the photoresist layer to the chromium mask layer before implementing chromium etching process.

After removing the remaining photoresist, the core layer pattern is transferred from chromium mask and structured via ICP etching. Finally, the chromium mask is removed and the over-cladding layer is deposited and consolidated. The detail of the fabrication process will be described in the next chapter.

Challenges for low loss PLC device fabrication depend on the quality of the waveguide channel. The critical processes depend mainly on pattern transfers by ICP etching where the waveguide channel and pattern appear. The quality of the waveguide pattern depends on the micromachining technique and etch parameters. Waveguides can be paradoxically simple yet complex to etch.

On the other hand, the metal masking comes as an important element of the etching process, where the etching condition for a compatible mask thickness needs to be considered. Many etching experimental works are carried on systematical testing and quantizing errors to find out the most suitable recipe for silica etching in this project. The surface and profile of waveguide channel are critical for fabricating the finest quality of PLC device.

Many waveguides act as wavelength splitters that compose of mixed wavelengths at the input with discrete wavelength outputs that are arrayed by channels. This, combining with fairly large propagation losses can result in comparatively meager light output at the waveguide channel splitting branch, which poses further challenges for some profile etch methodologies.

Achieving perfectly square and planar core profile at the waveguide channels can be frustrating, as this is often a time-consuming etching process. Fixturing and device non-reproducibility often complicate this fundamental initial task.

1.6 Objective

The main objective of this project is optimization of silica dry etching using fluorocarbon (C_xF_y) gas based parametric studies of the plasma conditions and drilling on Inductively Coupled Plasma (ICP) etching skills to achieve clean, good profile and high coupling efficiency of the waveguide channel. As to obtain low loss and good quality of waveguide channel, the operation of Inductively Coupled Plasma (ICP) etcher that include several parameters such as ICP RF power, Bias RF power and fed gas flow rate is studied. Additionally, the working pressure and etch duration are also analysed to achieve the appropriate etch depth of silica core layer.

1.7 Project Overview

In this project, PLC fabrication process is introduced to produce sophisticated PLC device which will be compatible with current optical networks. This is done by depositing and patterning silica waveguide circuit on a silicon substrate that consists of FHD system, vacuum furnace, DC Magnetron Sputter system, mask aligner and ICP etcher. The details of this process are given in the next chapter.

Chapter 3 presents the fundamental and mechanism of the etching process conducted in this project. This chapter will also include literature review and theory of the Inductively Coupled Plasma (ICP) etching.

Chapter 4 discusses the preliminary work concerning the experimental setup. This consists of ICP etch system and assessment that is carried on a silica core etching with two fluorocarbon gases namely CF_4 and C_2F_6 . Additionally, the measurement results are also demonstrated.

Chapter 5 summarizes the overall discussion of this project and gives some suggestions for future work.

References

- [1] E. Suhir, "Microelectronics and Photonics- The Future", *Microelectronics Journal*. vol. 31, pp. 839-851, 2000.
- [2] R. Morgan, "Options for High-Speed Transmission on Mixed-Grade Fiber Plant," *Lightwave*, pp. 140 –148 (August 2000).
- [3] G. E. Keiser, "A Review of WDM Technology and Applications," *Optical Fiber Techn.* **5**, 3–39 (1999).
- [4] W. Denzel and B. Meekers, "Photonics in the Backbone of Corporate Networks—The ACTS COBNET Project," *Proceedings of the European Conference on Networks and Optical Communications (NOC '97)*, IOS Press, Antwerp, Belgium, 1997, Part 3, pp. 225–232.
- [5] G. L. Bona, W. E. Denzel, B. J. Offrein, R. Germann, H. W. M. Salemink, and F. Horst, "Wavelength Division Multiplexed Add/Drop Ring Technology in Corporate Backbone Networks," *Opt. Eng.* **37**, 3218 –3228 (December 1998).
- [6] J. P. Ryan, "WDM: North American Deployment Trends," *IEEE Commun. Mag.*, pp. 40 – 44 (February 1998).
- [7] Ajoy Ghatak k. Thyagarajan, "Introduction to Fiber Optics", 1997.
- [8] Harry J.R.Dutton, "Understanding Optical Communications", Prentice Hall PTR, 1998.
- [9] Q. Lai, J. S. Gu, M. K. Smit, J. Schmit and H. Melchior, "Sample Technologies for Fabrication of Low-Loss Silica Waveguides", *Electronics Letter*, vol. 28, no.11, 1992.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses Planar Lightwave Circuit (PLC) fabrication techniques that are used to produce silica on silicon optical chips. Planar Lightwave Circuit (PLC) devices consist of transparent media that enable light to be guided in a transparent core layer which is sandwiched between two cladding layers. The cladding should have a lower index of refraction in order to steer the light in the core. Since the semiconductor processing technique implemented on integrated circuit fabrication is very well developed over the decade, an advance is obtained not only in research and development, but has also matured in commercialization and manufacturing line. These advantages have revolutionized PLC fabrication developments.

PLC is designed to enhance the telecommunication system performance and simplicity. The development and success of PLC fabrication will overcome the limit of the optical fibre to move forward and step closer to next generation telecommunications of Fibre-To-The-Premise (FTTP) and Fibre-To-The-Home (FTTH) which would enable high speed network. As the objective is to succeed the aim of high quality PLC devices, the fabrication process is analysed to master the technique.

For optimization of optical networks, component modules integration and manufacturing cost effectiveness is are required. This in turn, require subcomponent manufacturers to come out with production-worthy solutions. Silica-based PLCs are key components of functional devices that are designed for use in optical fibre communication systems. The reasons are because, compared to bulk optics and fibre-based devices, they offer compactness, excellent stability and reliability in addition to high functionality. Silica is particularly suitable as a base material for planar optical communication components as it is inherently compatible with optical fibres, resulting in low insertion and propagation losses as well as polarization insensitivity.

Silica-on-silicon planar waveguides are manufactured by deposition and subsequent etch patterning of silica layers on a silicon wafer. This process results in a channel of high refractive-index silica that is encased in the lower-index silica cladding. The waveguide core carries the lightwave through the desired path in optical devices in the same way that a metal track carries electrical signals in microelectronic circuits. Initially, this type of structure may not appear to be suitable for volume manufacturing by utilising standard semiconductor processes. However, with careful selection and some modifications, mass fabrication process of semiconductor can be adopted in planar waveguide fabrication.

The fabrication process begins with either deposition or growth of a buffer oxide layer, typically 15 μm to 20 μm thick on a silicon substrate. This is a much thicker dielectric layer than would be used for device isolation or gate dielectric in microelectronics processing. This might be seen as creating a major problem when attempting to fully automate the manufacturing of photonics materials. Conventional thermal oxide

growing method would require several weeks to achieve a silica layer of this thickness. Therefore, this opens up the exploration of alternative techniques for silica deposition.

Flame Hydrolysis Deposition (FHD) method has been adopted for thick silica film deposition. This process involves introducing the glass precursor chemicals into a hydrogen/oxygen torch flame, which hydrolyses the chemicals to form glass particles. These particles are deposited onto the wafer as a thick, porous layer that is then placed in a furnace for densification.

The next step involves the deposition of a core layer, typically 6 μm to 8 μm thick oxide layer on top of the buffer layer. By careful addition of dopants, such as germanium, boron and phosphorus, the core layer is engineered to have a higher refractive index than the buffer layer. The core is then masked and the waveguide pattern is defined by a reactive ion etch process, all of which are semiconductor processing techniques that are entirely conventional.

Finally, a silica cladding layer with a similar refractive index to the buffer is deposited over the etched core structure. Multiple steps may be required when cladding the core to ensure that the waveguide is covered completely and no voids are introduced within the structure. In all of the processes, it is critical to maintain uniform composition of the layer thickness and refractive indices to avoid propagation loss in the final device.

2.1 Fundamentals of Planar Lightwave Circuit Fabrication

Silicon is the standard substrate material for Integrated Circuit (IC) fabrication and, hence, the most common substrate material in micro-fabrication. It is supplied as single-crystal wafers with diameters between 100 and 300 mm. In addition to its favourable electrical properties, single-crystal silicon also has excellent mechanical properties, which enable the design of micromechanical structures. Complementary metal–oxide–semiconductor (CMOS) processes for digital electronics typically use low-doped silicon wafers, whereas processes for mixed-signal or analogue electronics are often based on high-doped wafers with a low-doped epitaxial layer to minimize latch-up.

High p-type doping substantially reduces the silicon etch rates in KOH solutions, thus preventing the use of highly p-doped CMOS substrates in combination with KOH etching. Instead of them, for PLC application is neither electrical nor mechanical properties of the wafer, whereas low-doped and high-doped wafers are both compatible for PLC fabrication process. Throughout this project, we have utilised 4 inch silicon wafer with single face polished and finished with thin thermal oxide layer as better thermal compatibility with silica deposition. Additionally, silica on silica PLC device is better and higher quality but it is constrained by cost.

Two successful glass making techniques in the development of optical waveguide technology include Chemical Vapour Deposition (CVD) and Flame Hydrolysis Deposition (FHD) [1]. In both of these two approaches, high purity chemicals such as SiCl_4 , GeCl_4 and POCl_3 have been used as precursors. Their high optical purity has been obtained by repeatedly distilling their vapours to exclude other contaminants. This is

possible because all of these chemicals are in liquid form and have a high vapour pressure. Another advantage of the chemicals with high vapour pressure is the ease of delivery of these chemicals into the reaction zone. The vapours of the chemicals can be easily transported and distributed over a large area with or without assistance of carrier gas. In a typical planar film deposition, a CVD process utilizes precursor chemicals that are reacted on a heated substrate to form dense glass films. In contrast an FHD process utilizes precursor reactants that are carried into a fuel and oxygen flame to form glass soot particles. These soot particles are immediately deposited onto a substrate. In both cases, a second step of thermal treatment is required to produce final glass with high optical properties. Typically, CVD needs an annealing process around 600 - 800 °C, whereas FHD needs a consolidation process around 1000 – 1300 °C. Initial optical integration at very limited scale has been achieved by making multi-channel devices based on commercial glass films product such as Arrayed Waveguide Gratings (AWG)[2][3].

The FHD process was developed and commercialized to produce glass films on planar substrates. Various optical films with functionalities including amplification, UV sensitivity and high transparency have been researched in the past. Active devices including lasers and amplifiers have been produced in various research efforts. One of the major advantages of this technique is that it has an intermediate stage after the glass soot deposition and before the consolidation. At this stage, the glass soot layer can be loaded with other dopants such as rare earth elements by using a solution doping technique that is developed for fibre-based devices. Another advantage of this technique is that it has very low stress formation during the soot deposition step. This is because the interaction

between the soot particles is a much weaker one compared with atomic bonding action occurred in the other deposited film as CVD and Plasma Enhanced Chemical Vapour Deposition (PECVD). High volumes of glass soot materials can be coated on the surface of planar substrates in FHD. Such volumes of glass soot materials can be subsequently converted into thick film by a thermal consolidation. Of course, proper selected materials composition, consolidation temperature, environmental gases, heating and cooling rates during consolidation are critical factors that must be controlled to obtain final optical quality glass.

A brief overview on the four basic micro-fabrication steps will be presented as the following.

2.1.1 Deposition

Thin-film deposition is a technique for depositing a thin film of material onto a substrate or previously deposited layers. "Thin" is a relative term, but most deposition techniques allow layer thickness to be controlled within a few tens of nanometres, and some (molecular beam epitaxy, MBE) allow single layers of atoms to be deposited at a time.

The technique is useful in the manufacture of optics for reflective or anti-reflective coatings, for instance, electronics such as layers of insulators, semiconductors, and conductors form integrated circuits, inclusive of packaging of aluminium-coated film and in contemporary art as well. Similar processes are sometimes used where thickness is not important: for instance, the purification of copper by electroplating and the deposition

of silicon and enriched uranium by a Chemical Vapour Deposition-like process after gas-phase processing.

Deposition techniques fall into two broad categories, depending on whether the process is primarily chemical or physical. Moreover, the hybrid deposition technique which combined both chemical and physical deposition techniques will also be described in the following.

2.1.1.1 Chemical Deposition

Chemical deposition implies a fluid precursor that undergoes a chemical change at a solid surface, thus leaving a solid layer. An everyday example is the formation of soot on a cool object when it is placed inside a flame. Since the fluid surrounds the solid object, deposition happens on every surface independently of direction because thin films from chemical deposition techniques tend to be conformal, rather than directional.

Chemical deposition is further categorized by the phase of the precursor whether in liquid, gas and ionized vapour or plasma. Chemical vapour deposition (CVD) generally uses a gas-phase precursor, often a halide or hydride of the element to be deposited. In the case of Metal Organic Chemical Vapour Deposition (MOCVD), an organometallic gas is used. Commercial techniques often use very low pressures of precursor gas. Other than CVD and MOCVD, FHD is also designed as a chemical deposition system where the helium gas acts as a carrier gas to deliver other chemicals in gas form and reacts in oxy-hydrogen flame. In the glass deposition process, the halide

mixture gases are heated at quartz torch by oxy-hydrogen flame to form silica soot on the wafer.

Plasma enhanced Chemical Vapour Deposition (PECVD) uses an ionized vapour, or plasma, as a precursor. Unlike the soot example above, commercial PECVD relies on electromagnetic means (electric current, microwave excitation), rather than a chemical reaction, to produce a plasma.

2.1.1.2 Physical Deposition

Physical deposition uses mechanical or thermodynamic means to produce a thin film of solid. An everyday example is the formation of frost. Most engineering materials are held together by relatively high energies and chemical reactions are not used to store these energies. This results in commercial physical deposition systems tend to require a low-pressure vapour environment to work properly which can be classified as Physical Vapour Deposition (PVD).

The material to be deposited is placed in an energetic, entropic environment in order for particles of the material escape its surface. Facing this source is a cooler surface which draws energy from these particles as they arrive, allowing them to form a solid layer. The whole system is kept in a vacuum deposition chamber that leads the particles to travel as freely as possible. Since particles tend to follow a straight path, films deposited by physical means are commonly directional, rather than conformal.

Examples of physical deposition include a thermal evaporator that employs an electric resistance heater to melt the material and raise its vapour pressure to a useful

range. This is done in a high vacuum, both to allow the vapour to reach the substrate without reacting or scattering against other gas-phase atoms in the chamber. As a result, these reduce the incorporation of impurities from the residual gas in the vacuum chamber. Obviously, only materials with a much higher vapour pressure than the heating element can be deposited without contamination of the film. Molecular beam epitaxy is a particular sophisticated form of thermal evaporation.

An electron beam evaporator fires a high-energy beam from an electron gun to boil a small spot of material. Since the heating is not uniform, lower vapour pressure materials can be deposited. The beam is usually bent through an angle of 270° in order to ensure that the gun filament is not directly exposed to the evaporant flux. Typical deposition rates for electron beam evaporation range from 1 to 10 nanometres per second.

Another technique is called sputtering. The technique relies on the glow discharge that is usually a noble gas namely argon plasma to knock material from a "target" a few atoms at a time. The target can be kept at a relatively low temperature since the process is not evaporation-orientated, thus making this as one of the most flexible deposition techniques. It is especially useful for compounds or mixtures, where different components would otherwise tend to evaporate at different rates. Sputtering step coverage is more or less conformal.

Pulsed laser deposition systems work by an ablation process. Pulses of focused laser light vaporize the surface of the target material and convert it into plasma where this plasma usually reverts to a gas before reaching the substrate.

2.1.1.3 Other Deposition Techniques

Some methods fall outside the chemical and physical deposition categories, relying on a mixture of chemical and physical means. In reactive sputtering, a small amount of some non-noble gases, for instance oxygen or nitrogen are mixed with the plasma-forming gas. After the material is sputtered from the target, it reacts with these gases that leads the deposited film to be converted into an oxide or nitride of the target material.

In Molecular Beam Epitaxy (MBE), slow streams of an element can be directed to the substrate to deposit one atomic layer at a time. Compounds such as gallium arsenide (GaAs) are usually deposited by repeatedly applying a layer of an element (i.e., Ga) before applying another layer (i.e., As) that results in the process to involve chemical as well as physical reaction. The beam of the material can be generated by utilising either physical means that incorporate a furnace or by a chemical reaction which is known as chemical beam epitaxy.

In topotaxy that is a specialized technique similar to epitaxy, a thin film crystal growth occurs in three dimensions due to the crystal structure similarities either in compound (heterotopotaxy) or an element (homotopotaxy) between the substrate crystal and the growing thin film.

2.1.2 Doping / Ion Implantation

A dopant, also called as doping agent is an impurity that is added to a semiconductor lattice in low concentrations to alter the optical or electrical properties of the semiconductor. In solid-state lasers, the most common “dopants” are ceramics, glasses and of crystalline-based such as Yb, Er, Nd, Tm, Ce. In many optically-transparent hosts, such active ions may keep their excitation time in the order of millisecond, relax and producing stimulated emission to provide the laser action. The amount of dopant is usually measured in atomic percent where the dopant ion can only substitute the appropriate site in a crystalline lattice. The doping can also be used to change the refractive index in optical fibres, especially in the double-clad fibres and PLC core layer. The main parameters of an active dopant are characterized by lifetime of excitation and effective absorption and emission cross-sections. Usually the concentration of an optical dopant is in the order of a few percent or even lower. At large density of excitation, the cooperative quenching or cross-relaxation reduces the efficiency of the laser action.

2.1.3 Patterning / Photolithography

Photolithography is a pattern transfer process in micro-fabrication where it selectively remove parts of a thin film or the bulk of a substrate. It is also known as optical lithography because it uses light to transfer a geometric pattern from a photomask to a light-sensitive chemical which is called photoresist (PR) or "resist" on the substrate.

A series of chemical treatments then engraves the exposure pattern into the material underneath the photoresist layer. In a complex integrated circuit for example, modern Complementary Metal–Oxide–Semiconductor (CMOS), a wafer will go through the photolithographic cycle for up to 50 times.

Photolithography resembles the conventional lithography that is used in printing and shares some fundamental principles with photography. It is used because it can afford exact control over the shape and size of the objects that it creates and also create patterns over an entire surface simultaneously. Its main disadvantages are that it requires a flat substrate to start with, its' inefficiency at creating shapes that are not flat, and the requirement for extremely clean operating conditions. In addition, the photolithography process needs to be run under yellow room to reduce unwanted ultraviolet (UV) exposure.

Photomask has been designed with computer-aided-engineering (CAE) software packages on to a certain material. The mask is a glass plate with a patterned opaque layer typically consisting of chromium on the surface. Electron-beam lithography is employed to write the mask pattern from the CAE data. In the photolithographic process, a photostructurable polymer or PR layer is spin-coated on to the material to be writtended[4].

Next, the PR layer is exposed to ultraviolet (UV) light through the mask. This step is done in a mask aligner, in which mask and wafer are aligned with each other before the subsequent exposure step is performed. Depending on the mask aligner generation, mask and substrate are brought in contact or close proximity, or the image of the mask is projected onto the photoresist-coated substrate. In addition, the exposed or

the unexposed PR areas are removed during the resist development process [4] depending on whether positive or negative PR was used. The positive type photolithography process sequence is illustrated in Fig. 2.1.

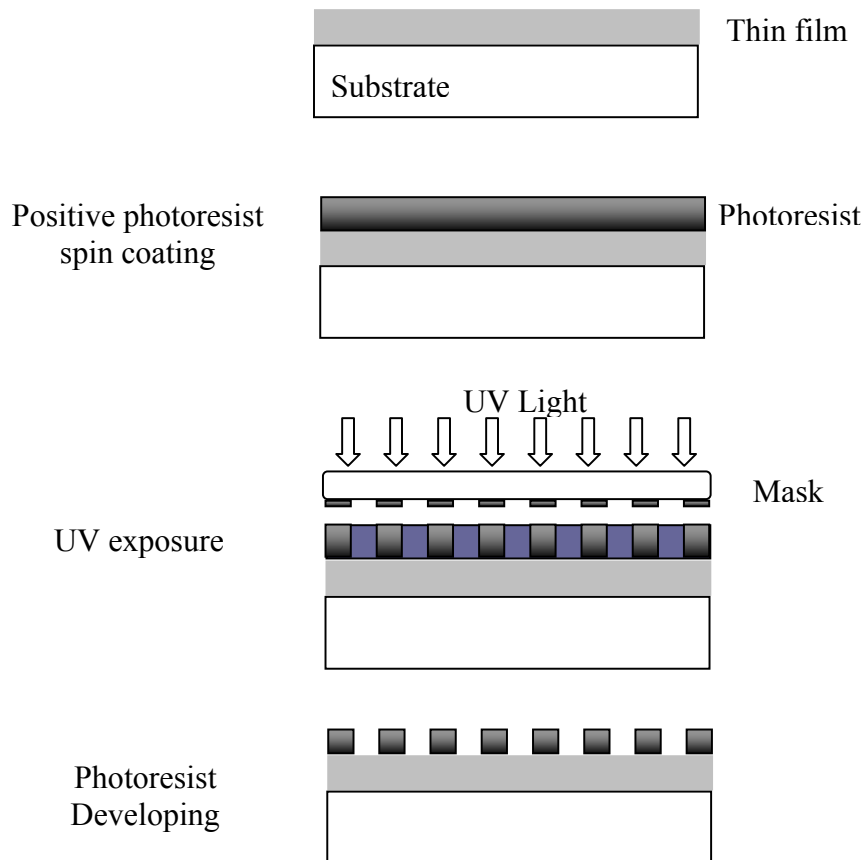


Figure 2.1: Schematic of a positive type photolithographic process sequence

The remaining PR acts as a protective mask during the subsequent etching process, which transfers the pattern onto the underlying material. Alternatively, the patterned PR can be used as a mask for a subsequent ion implantation [4].

After the etching or ion implantation step, the remaining PR is removed and the next layer can be deposited and written. The so-called lift-off technique in semiconductor

processing is used to structure a thin-film material, which would be difficult to etch. Here, the thin-film material is deposited on top of the patterned PR layer. In order to avoid a continuous film, the thickness of the deposited film must be less than the resist thickness. By removing the underneath PR, the thin-film material on top is also removed by “lifting it off”, thus leaving a structured thin film on the substrate.

2.1.3.1 Basic Procedure

A single iteration of basic photolithography procedure combines several steps in sequence. Modern clean rooms consist of automated, robotic wafer track systems to coordinate the process. The procedure described here omits some advanced treatments such as thinning agents or edge-bead removal [5]. In the preparation stage, the wafer is initially heated to a temperature that is sufficient to drive off any moisture that may be present on the wafer surface. Wafers that have been in storage must be chemically cleaned to remove contamination. Optionally, a liquid or gaseous "adhesion promoter" such as hexamethyldisilazane (HMDS) is applied to promote adhesion of the photoresist to the wafer. But the handling and awareness of the toxicity of the chemical like HMDS needs to be taken carefully.

For PR application, the wafer is covered with PR by spin coating. A viscous, liquid solution of photoresist is dispensed onto the wafer, and the wafer is spun rapidly to produce a uniformly thick layer. The spin coating typically runs at 4000 to 8000 rpm for 30 to 60 seconds, and produces a layer between 0.5 and 2.5 microns thickness. The photoresist-coated wafer is then soft-baked or prebaked to drive off excess solvent, typically at 90 to 110 °C for 2 to 5 minutes. Sometimes this process is done by involving

a nitrogen atmosphere. After soft-baking, the photoresist is exposed to a pattern of intense light where in optical lithography it is typically ultraviolet (UV) light. Positive photoresist that is the most common type, becomes less chemically robust when exposed whereas negative photoresist becomes more robust under the same condition. This chemical change allows some of the photoresist to be removed by a special solution that is called developer in a full analogy to the photographic developer. A post-exposure bake is performed before developing, typically to help reduce standing wave phenomena that is caused by the destructive and constructive interference patterns of the incident light.

The developed solution is delivered on a spinner, much like photoresist. Developers originally often contain sodium hydroxide (NaOH). However, sodium is considered an extremely undesirable contaminant in MOSFET fabrication because it degrades the insulating properties of gate oxides. Metal-ion-free developers such as tetramethylammonium hydroxide (TMAH) are now used. The resulting wafer is then "hard-baked", typically at 100 to 130 °C for 10 to 30 minutes. The hard bake solidifies the remaining photoresist to make a more durable protecting layer in future ion implantation, wet chemical etching, or plasma etching.

In the case of metal masking, chromium etching is proceeded to transfer the pattern from PR to chromium after PR is developed. Detail of chromium etching will be described during chromium wet etching process. After a photoresist pattern is no longer needed, it must be removed from the substrate. This usually requires a liquid resist stripper, which chemically alters the resist so that it no longer adheres to the substrate. Alternatively, photoresist may be removed by a plasma containing oxygen, which oxidizes it. This process is called ashing, and resembles dry etching.

For exposure systems, an image is typically produced on the wafer by incorporating a photomask. The light shines through the photomask, which blocks it in some areas and lets it pass in others. Instead of this, maskless lithography projects a precise beam directly onto the wafer without using a mask, but it is not widely implemented in commercial processes. Exposure systems may be classified by the optics that transfer the image from the mask to the wafer.

2.1.3.2 Lithography

The photomask is a very important component in photolithography. The image of the mask originates from a computerized data file. This data file is converted to a series of polygons and written onto a square fused quartz substrate that is covered with a layer of chrome by using a photolithographic process. A beam of electrons is used to expose the pattern defined in the data file and travels over the surface of the substrate in either a vector or raster scan manner. While the photoresist on the mask is exposed, the chrome can be etched away, leaving a clear path for the light in the stepper/scanner systems to travel through.

Three types of lithography are common in industry and research field namely contact, proximity and projection lithography. A contact printer that is the simplest exposure system puts a photomask in direct contact with the wafer before exposes it to a uniform light. In contrast, a proximity printer puts a small gap between the photomask and wafer. In both cases, the mask covers the entire wafer and simultaneously writes every die. The contact printing is liable to damage for both the mask and the wafer. Both contact and proximity lithography require the light intensity to be uniform across an

entire wafer and the mask to meet precise alignment with features already on the wafer. As modern processes use increasingly large wafers, these conditions become increasingly difficult.

The first integrated circuits had features of 200 micrometres which were printed when using contact lithography. This technique was popular in the 1960s until it was substituted by the proximity printing. This technique had poorer resolution than the contact printing (due to the gap that allows more diffraction to occur) but generated far less defects. The resolution was sufficient down to 2 micrometre production. In 1978, the step-and-repeat projection system appeared [6]. The platform gained wide acceptance due to the reduction of the mask image and it is still in use today.

The contact lithography is still commonly practiced today, mainly in applications requiring thick photoresist and/or double-sided alignment and exposure. Advanced 3D packaging, optical devices, and micro-electromechanical system (MEMS) applications fall into this category. In addition, the contact platform is the same as that used in imprint processes. Recently, two developments have given contact lithography a potential for comeback into semiconductor area. First, surface plasmon resonance enhancements including the use of silver films as lenses have been demonstrated to give resolution of less than 50 nm for wavelength sources of 365 and 436 nm [7]. Second, nanoimprint lithography has already gained popularity outside the semiconductor sector (eg, hard-drive and biotechnology) and it is a candidate for sub-45 nm semiconductor-based technique. These drive defect reduction practices and uniformity improvement for masks in contact with the substrate. Step-and-flash imprint lithography (SFIL) is a popular

method that involves UV curing of the imprint film which essentially uses the same setup as the contact lithography.

Commonly contact mask have several types such as standard binary intensity amplitude mask, light coupling mask, and hybrid nanoimprint. The standard binary intensity amplitude mask defines dark and light areas where the light is blocked or transmitted, respectively. The dark areas are patterned films consisting of chromium or other metals. The light coupling mask has a corrugated dielectric surface where each protrusion acts as a localized waveguide [8]. The light is transmitted primarily through the protrusions as a result of this localized guiding effect. Since less contact area is needed, there is less potential for defects. A hybrid nanoimprint-contact mask utilizes both contact imaging and mechanical imprinting [9], and has been proposed to optimize imaging of both large and small features simultaneously by eliminating imprint residual layer issues. Contact masks have traditionally been fairly large (>100 mm), but it is possible that alignment tolerances may require smaller mask sizes to allow stepping between exposures. As in the nanoimprint lithography, the mask needs to have roughly the same feature size as the desired image. Contact masks can be formed directly from other contact masks, or by direct writing (eg, electron beam lithography).

Research and prototyping processes often use contact lithography, because it uses inexpensive hardware and can achieve high optical resolution. The resolution is approximately the square root of the product of the wavelength and the gap distance. Hence, contact printing offers the best resolution because its gap distance is approximately zero (neglecting the thickness of the photoresist itself). In addition,

nanoimprint lithography may revive interest in this familiar technique especially since the cost of ownership is expected to be low.

The projection exposure system is also known as stepper. Very-large-scale integration lithography uses projection systems. Unlike contact or proximity masks which cover an entire wafer, projection masks that are also called as reticles show only a die. Projection exposure systems project the mask onto the wafer for many times to create the complete pattern. The ability to project a clear image of a small feature onto the wafer is limited by the wavelength of the light that is used and the ability of the reduction lens system to capture enough diffraction orders from the illuminated mask. Current state-of-the-art photolithography tools use deep ultraviolet (DUV) light with wavelength sources of 248 and 193 nm, which allow minimum feature sizes down to 50 nm.

The minimum feature size that a projection system can print is given approximately by:

$$F = k \cdot \frac{\lambda}{N_A} \quad (2.1)$$

where F is the minimum feature size, k is a coefficient that encapsulates process-related factors and typically equals to 0.5, λ is the wavelength of the light used and N_A is the numerical aperture of the lens as seen from the wafer.

According to this equation, minimum feature sizes can be increased by decreasing the wavelength and increasing the numerical aperture, for instance by making lenses larger and bringing them closer to the wafer. However, this design method runs into a competing constraint. In modern systems, the depth of focus is also shown as:

$$D_F = 0.6 \times \frac{\lambda}{N_A^2} \quad (2.2)$$

The depth of focus restricts the thickness of the photoresist and the depth of the topography on the wafer. Chemical mechanical polishing is often used to flatten topography before high-resolution lithographic steps.

2.1.3.3 Light Sources

Historically, light sources for photolithography comprise of ultraviolet light from gas-discharge lamps that incorporate mercury, sometimes in combination with noble gases especially xenon. These lamps produce light across a broad spectrum with several strong peaks in the ultraviolet range. This spectrum is filtered to select a single spectral line, usually the "g-line" (436 nm) or the "i-line" (365 nm). More recently, lithography has moved to "deep ultraviolet" that produces wavelengths below 300 nm from excimer lasers. For instance, Krypton fluoride produces a 248-nm spectral line and argon fluoride a 193-nm line.

Optical lithography can be extended to feature sizes below 50 nm when utilizing 193 nm wavelength source and liquid immersion techniques. Also termed as immersion lithography, this enables the use of optics with numerical apertures exceeding 1.0. The liquid used is typically ultra-pure, deionised water, which provides a refractive index that is above the usual air gap between the lens and the wafer surface. This is continually circulated to eliminate thermally-induced distortions. Water will only allow NA's of up to ~1.4, but materials with higher refractive indices will allow the effective NA to be increased further.

Tools that includes 157 nm wavelength DUV in a manner that is similar to current exposure systems have been developed. These were once targeted to succeed those that incorporate 193 nm laser sources with 65 nm feature size node, but have now been eliminated by the introduction of immersion lithography. This was due to persistent technical problems with the 157 nm-based technology and economic considerations that provide strong incentives for the continuing use of 193 nm-based technology. High-index immersion lithography is the newest extension of 193 nm lithography to be considered. In 2006, features less than 30 nm were demonstrated by IBM when implementing this technique[10].

2.1.3.4 Operating Principle

Upon exiting the photomask-photoresist interface, the image-forming light is subject to near-field diffraction as it propagates through the photoresist. Diffraction causes the image to lose contrast with increasing depth into the photoresist. This can be explained by the rapid decay of the highest-order evanescent waves with increasing distance from the photomask-photoresist interface. This effect can be partly mitigated by using thinner photoresist. Contrast enhancements based on plasmon resonances and lensing films have recently been disclosed [7]. The chief advantage of contact lithography is the elimination of the need for complex projection optics between the object and image. The resolution limit in today's projection optical systems originates from the finite size of the final imaging lens and its distance from the image plane. More specifically, the projection optics can only capture a limited spatial frequency spectrum

from the object (photomask). The contact printing has no such resolution limit but it is sensitive to the presence of defects on the mask or on the substrate.

2.1.3.5 Resolution and Image Quality Enhancements

As noted above, thinner photoresist can help improve image contrast. Reflections from the layer underlying the photoresist also have to be taken into account when absorption and evanescent wave decay are reduced.

The resolution of contact lithography has been predicted to surpass $\lambda/20$ periodicity [11]. The pitch resolution of contact lithography can be readily enhanced by multiple exposures that generate feature images between previously exposed features. This is suitable for nested array features, as in memory layouts.

Surface plasmons are collective oscillations of free electrons that are confined to metal surfaces. They couple strongly to light, forming surface plasmon polaritons. Such excitations effectively behave as waves with very short wavelength (approaching the x-ray regime). By exciting such oscillations under the right conditions, multiple features can appear in between a pair of grooves in the contact mask [12]. The resolution achievable by surface plasmon polariton standing waves on a thin metallic film is <10 nm with a wavelength in the 380-390 nm range when employing a <20 nm silver film [408]. In addition, deep narrow slits in metallic transmission gratings have been shown to allow resonances that amplify the light that passes through the slits [13].

A layer of metal film has been proposed to act as a 'perfect lens' for amplifying evanescent waves that results in enhanced image contrast. This requires tuning the

permittivity to have a negative real part, for instance a silver at 436 nm wavelength [14]. The use of such lens allows imaging to be achieved with a wide tolerance of distance between mask and photoresist. In addition, extreme resolution enhancement can be achieved when incorporating surface plasmon interference namely a half-pitch of 25 nm at 436 nm wavelength [14]. The perfect lens effect is only effective for certain conditions, but allows a resolution roughly equal to the layer thickness [15]. Hence a sub-10 nm resolution appears feasible with this approach as well.

The use of surface plasmon interference gives an edge over other lithography techniques. This is because the number of mask features can be much less than the number of features in the desired image, thus making the mask easier to fabricate and inspect [12, 16]. While silver is the most commonly used metal for demonstrating surface plasmons for lithography, aluminum has also been used at 365 nm wavelength [17]. As these resolution enhancement techniques allow 10 nm features to be contemplated, other factors must be considered for practical implementations. The most fundamental limitation appears to be photoresist roughness which becomes predominant for shorter sub-wavelength periods, where only the zeroth diffraction order is expected to propagate [7]. In this case, all the pattern details are conveyed by the evanescent waves which decay more rapidly for finer resolution. As a result, the photoresist's inherent roughness that follows this development can become more significant than the pattern.

Since image quality is a function of both focus and exposure dose, such resolutions are obtained in part by minimizing the resist thickness and limiting the interference from underlying features [18]. The trend toward reduction in resist thickness

places limitations on the amount of material which can be removed during etching process.

2.1.4 Etching

The two different categories of etching processes include wet etching that utilises liquid chemicals and dry etching that utilises gas-phase chemistry. Both methods can be either isotropic which provide the same etch rate in all directions, or anisotropic which provide different etch rates in different directions. The important criteria for selecting a particular etching process encompass the material etch rate, the selectivity for the material to be etched, and the isotropy or anisotropy of the etching process [4].

Wet etching is usually isotropic with the important exception of anisotropic silicon wet etching in, as an example alkaline solution of potassium hydroxide. Moreover, wet etching typically provides a better etch selectivity for the material to be etched in comparison to other neighbouring materials. An example includes wet etching of silica that is known as silicon dioxide (SiO_2) that employs hydrofluoric acid-based chemistries. Silica is isotropically etched in dilute hydrofluoric acid ($\text{HF-H}_2\text{O}$) or buffered oxides etch, BOE ($\text{HF-NH}_4\text{F}$). Typical etch rates for high-quality (thermally grown) silicon dioxide films are $0.1 \mu\text{m/min}$ in BOE [4].

Dry etching, on the other hand is often anisotropic that results in a better pattern transfer as mask under-etching is avoided. Therefore, anisotropic dry etching processes especially reactive ion etching (RIE) of thin-film materials are very common in the microelectronics industry. In an RIE system, reactive ions are generated in plasma and

are accelerated towards the surface to be etched, thus providing directional etching characteristics. Higher ion energies typically result in more anisotropic etching characteristics, but also in reduced etching selectivity [4].

2.2 Fabrication Equipments and Tools

PLC devices fabrication requires complete facilities inclusive of clean room, specific fabrication equipments that comprise of Flame Hydrolysis Deposition (FHD) System together with Wet Scrubber for silica glass deposition. Other facilities are such as Vacuum Furnace for glass soot consolidation, Direct Current (DC) Magnetron Sputter System for chromium deposition, UV Mask Aligner with appropriate photomask for Optical Planar Waveguide device pattern transfer and Inductively Coupled Plasma (ICP) Dry Etching System for silica glass etching. Sometimes, the Wet-bench is also included for wafer handling and wet chemical etching process. Further description of fabrication and measurement equipments will also be presented in the following.

2.2.1 Flame Hydrolysis Deposition System

The FHD System is designed for high deposition rate of silica thick film on the silicon wafer to fabricate optical Planar Lightwave Circuit (PLC) components. These are Splitter, Coupler, Optical Add and Drop Multiplexer (OADM) and Array Waveguide Grating (AWG) which are the key components of optical Wavelength Division Multiplexing (WDM) transmission network. It also combines high productivity,

simplicity of operation through full automation, maximum safety and easy access for maintenance.

An FHD deposition system that is capable of handling four-inches wafers is used to grow waveguide films with thickness from one micron to 400 micron. The films can be doped with Boron, Phosphorus, and Germanium to control the refractive index with a precision better than 10^{-4} .

Silica porous soot is doped with Boron (B) in the semiconductor industry as boron play important roles as light structural materials, non-toxic insecticides and preservatives, and reagents for chemical synthesis. For instance, Boron is used as a melting point depressant in silica composite to reduce temperature in soot consolidation process but also lower the refractive index of the silica layer. On the other hand, POCl_3 is used as a safe liquid phosphorus source in diffusion processes. In the semiconductor industry, phosphorus acts as a dopant that is used to create N-type layers on a silicon wafer. Addition of germanium, phosphorus and boron to the silica enables the refractive index and glass transition temperature of the oxide to be modified. In fact, high temperature annealing results in a decrease of the refractive index and an increase in the inhomogeneity of the refractive index in the vertical direction but somehow out-diffusion of phosphorus plays a role to reduce compressive stresses in the films [19].

Germanium (Ge) is also a dopant that is added to increase refractive index of the silica core layer. Theoretically, germanium dioxide (GeO_2) refractive index is about 1.7 and optical dispersion properties make it useful as an optical material for wide-angle lenses and in optical microscope objective lenses. Germanium dioxide is transparent in the infrared and it is heated with powder germanium at 1000 °C to form germanium

mono-oxide (GeO). Mixture of silicon dioxide and germanium dioxide (silica-germania) is used as an optical material for optical fibres and optical waveguides. Controlling the ratio of the elements allows precise control of refractive index. Silica-germania glasses have lower viscosity and higher refractive index than the pure silica. Germania replaced titania as the silica dopant for silica fibre, eliminating the need for subsequent heat treatment which made the fibres brittle. The fibre was then heated for about three hours in an oxygen atmosphere to restore the valence of the titania to its low-loss state. The cladding had a refractive index of about 0.5 percent lower than the core, and the fibre carried a single light mode with an attenuation in the signal of about 16 dB/km.

FHD System comprises of 3 major parts that are delivery, reactor, and pc control. The Delivery System consists of chemicals, gases mixture and piping for handling and delivering the chemicals to a reactor chamber. The Reactor is a place where the chemical reaction and deposition processes occur. And finally, PC Control scheme controls and monitors the whole process of FHD System

2.2.1.1 FHD Delivery System

FHD Delivery System is connected to the chemical cylinders where handling and preparing of the process reagents (gases and chemicals) are carried out in the stainless steel piping. These are then delivered to the Reactor System via bubbler that controls their mixture. The bubbler consists three main parts, the first part houses gas circuit including the Mass Flow Controller (MFC) and their associated pneumatic control valves as well as the temperature regulation system for the bubblers thermostatic oil bath.

The second part is the ultra dry glove box. It houses all electro-polished pipe work, valves and mixing manifolds. The automatic bubbler refill pipe work and valves are also located in this section.

The third part is electrical control section that houses the control system, switch mode power supplies, ultra dry glove box, oil bath temperature controllers, and the interfaces for all the controlled parts of the FHD System.

An optimized gas circuit design is based on theoretical calculation and practical operation. The specified tube size is calculated for optimum flow to every part of gas circuit. The nature of the chemicals utilized in PLC manufacturing process makes selection of materials for the piping and valves to be critical, if reaction with or contamination of the gaseous and liquid reagent is to be avoided.

The valves, filters, pressure regulators and electro-polished circuit handle gases filtration, distribution and flow control from the gas inlets of the cabinet to the Jungle Box bulkheads. High quality components and high integrity pipe work enable the leak rate of less than 1×10^{-9} cc/second He to be assured for safety purpose. A high performance switch mode power supply is used in conjunction with a feedback set point signal to optimize the electrical control. This leads to the production of fine product on a mass production basis.

The Delivery System is equipped with manual valves for isolating the gas inputs upstream of each flow controller. The MFC is an important parameter to study the experiment of FHD on silica deposition. Typical MFC specifications are given as the following:

Flame Gas

Oxygen	: up to 20000 sccm
Hydrogen	: up to 5000 sccm
Helium (Mixture)	: up to 5000 sccm
Helium (Shield)	: up to 5000 sccm

Chemical Feed

Helium (SiCl_4)	: up to 100 sccm
Helium (GeCl_4)	: up to 100 sccm
Helium (POCl_3 , large)	: up to 100 sccm
Helium (POCl_3 , small)	: up to 20 sccm
BCl_3 (large)	: up to 200 sccm
BCl_3 (small)	: up to 20 sccm

Mass Flow Meter

MFM	: up to 2000 sccm
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The non-bubbler channels are switched by pneumatic bellows valves on the MFC gas panel. All these gases are fixed with an ON / OFF function downstream of the MFC. The channels for corrosive toxic gases that consist of chlorine and spare corrosive gas are equipped with local nitrogen which is gas switching upstream and run or vent switching downstream of the MFC. Check valves are used where it is necessary to ensure that no back streaming of corrosive or toxic reagent gases to get into carrier gas lines.

Valves and connections are fixed for gas flow sampling of all channels and volumetric flow calibration. The valves and standard steel circuit carry corrosive halide, as well as vapours entrained in a stream of oxygen for deposition.

In the ultra dry gas box, it is constructed by incorporating an inner welded standard steel box. The outer box of powder-painted is employed, with a barrier of heat insulation materials between the two. The design is ensured both to have low internal moisture levels and a minimal rise in outer wall temperature. The window is secured against its “O” ring seat by a ring of quickly detachable clamps. When released, these allow the window to be easily lifted out to provide access to the dry box interior. Limited access without window removal is possible via two glove ports.

The unit houses oil baths containing quartz bubblers, valves, piping and mixing manifolds. Nitrogen is supplied to this unit from the gas bay with an appropriate purity for achieving very low moisture levels inside the dry box. A continuous purge is maintained with a bleed to vent via an oil trap. The nitrogen inside the dry box may be thermostatically controlled from around 6 °C above the ambient and up to 60 °C, allowing the bubblers to operate at elevated temperatures without re-condensation of halide vapour in the downstream pipe work. The dry environment is extended right up to the perform reactor by the incorporation of umbilical link in which the reagents pass down the central tube with electrical heating elements.

The oil baths are constructed with stainless steel and the window is purposely for bubbler viewing and inspection. Oil bath houses the GeCl_4 bubbler (3 litres), POCl_3 (1 litre) and SiCl_4 bubbler (10 litres) and temperature of the operating range is 15 °C ~ 55 °C. For safety issue, the front window is made of toughened glass construction with high integrity flange seal to prevent leaking. It is deliberately not doubled glazed to increase heat flux, which allows more precise control of dry box temperature close to ambient levels.

In the electrical control section, the electric controller and oil circulation system give independent temperature control of the baths. A resistance thermometer mounted in each oil bath and Proportional/Integral/Derivative (PID) electrical power control unit are used to drive the bath heater, indicate temperature and feature the out-of-limit alarms. This heater works in opposition to a continuously running chiller unit, which is situated with the heater-circulating pump and oil reservoir in the frame module below the Dry Box. Ventilation cowls are used to duct cooling air through the chiller to reduce temperature of the area.

2.2.1.2 FHD Reactor System

In the reactor chamber, the gases mixture and vaporized chemicals supplied from Delivery System are heated at quartz torch by oxy-hydrogen flame to produce soot and it's deposited on the wafer mounted upon turntable. After deposition process is over, the wafer transferred to the furnace for further sintering process.

There are two main parts which are reactor chamber and the torch assembly system. Reactor chamber is the isolated atmosphere for optimized deposition process which consists of turntable with highly stable rotation movement. The torch assembly system is charged with straight-line motion, controlled by AC Servo Motor with 0.02 mm repeating accuracy. The seal between torch modules and chamber inside which are coated to constrict corrosion affected by erosive gas and particle. During deposition process, both of the turntable and torch need high precision position control of both axes with excellent speed stability, which are moving automatically with the assigned mode to control the thickness and uniformity of the deposition process.

In the FHD Reactor System, residuary gases and particles are blown out by the exhaust system during deposition process. The exhaust fume ducts equipped with damper for pressure controlling and turntable is built-in the thermostat to heat up wafer at preset temperature, both of them also play an important role in deposition process condition.

2.2.1.3 PC Control System

The control system is based on a rugged PC and it is used to control all functions of the delivery and reactor system. Control of the torch assembly and turntable motor mounted in the reactor chamber, which communicate with the PC via separate serial interface links. Manual control of the torch assembly and turntable motor is also possible via a remote control box at reactor.

The FHD System is using Laboratory Virtual Instrument Engineering Workbench (LabVIEW) graphical program to set, control and run the deposition process recipe and parameter via PC Control System. In the PC Control System, there are four sorts of motion profile option to assign the torch and turntable motion accordingly as “Constant”, “Linear”, “1/R” and “PS Constant”. Additionally, the motion simulation enables the real time display of duration, speed and location.

The PC Control System program consists of six main graphical user interface as shown below:

- 1) FHD Main Window : Display all features and settings
- 2) Trend Window : Display the variation as the change of torch location
- 3) Piping Window : Display pipe and maintenance condition
- 4) System Window : Display system variable

5) Refill Set Window : Display chemical refill condition

6) Dry Motion : Display dry motion test

Flame hydrolysis deposition (FHD) is a chemical process that is developed for optical fibre manufacture and modified to suit planar waveguide fabrication. Halides are hydrolysed in an oxy-hydrogen flame to produce oxides in soot form, which are deposited on silicon substrates. The soot is then sintered to produce the planar silica layer by furnace.

Using this process it is possible to accurately control both the thickness and the refractive index of the layer that is typically matched to optical fibre cores. These can be made single or multi mode by design. Once the core layer has been grown, it can be written by employing standard photolithographic processes, metal masking and dry etched. Then, cladding layers can be deposited to suit application by repeated deposition and consolidation process. Finally, the devices can be cut to size and polish for butt end coupling or lens alignment and packaging depending on requirements.

Flame hydrolysis deposition (FHD) is an effective means of producing thick films at low production cost and the glass layer can be loaded with other dopants such as Ge, B, and Ti [20–24]. From a series of tests and analyses, the excellent silica films recipe for Planar Lightwave Circuit (PLC) fabrication is found out. Consequently, it proves that SiO₂ films prepared by FHD are entirely capable to be applied in planar optical waveguides [25]. SiO₂ film is synthesized by flame hydrolysis reaction in an oxy-hydrogen torch using metal halides such as SiCl₄, POCl₃ and BCl₃ as starting materials [26]. Boron-phosphosilicate glass (SiO₂-B₂O₃-P₂O₅) or BPSG that has a refractive index identical to fused silica is generally used for cladding layers [27].

2.2.1.4 Wet Scrubber

The Wet Scrubber system is an important supplementary component which is designed to neutralize chlorine that is produced or wasted and extracted by entrained air draft. The scrubbing system is operated under negative pressure which is generated by separate extraction fan for the sufficient pressure and flow. This fan is connected to main exhaust system from 80 liter foot tank by using caustic water or sodium peroxide (NaOH) solution. The Wet Scrubber system is maintained in less than 1 ppm of HCl and chlorine at the outlet, which may be safely vented to the atmosphere.

The main Wet Scrubber unit comprises of a PVC tank that is housed by a steel framed PVC cabinet. Gas inlet and outlet ports of the tank are on the top surface of the cabinet. Effluent gases from the FHD process are mixed with unconsolidated oxide soot particles. These are then washed by a fine spray of caustic water solution which is pumped from the reservoir in the tank base, filtered and forced through jets in the tank root.

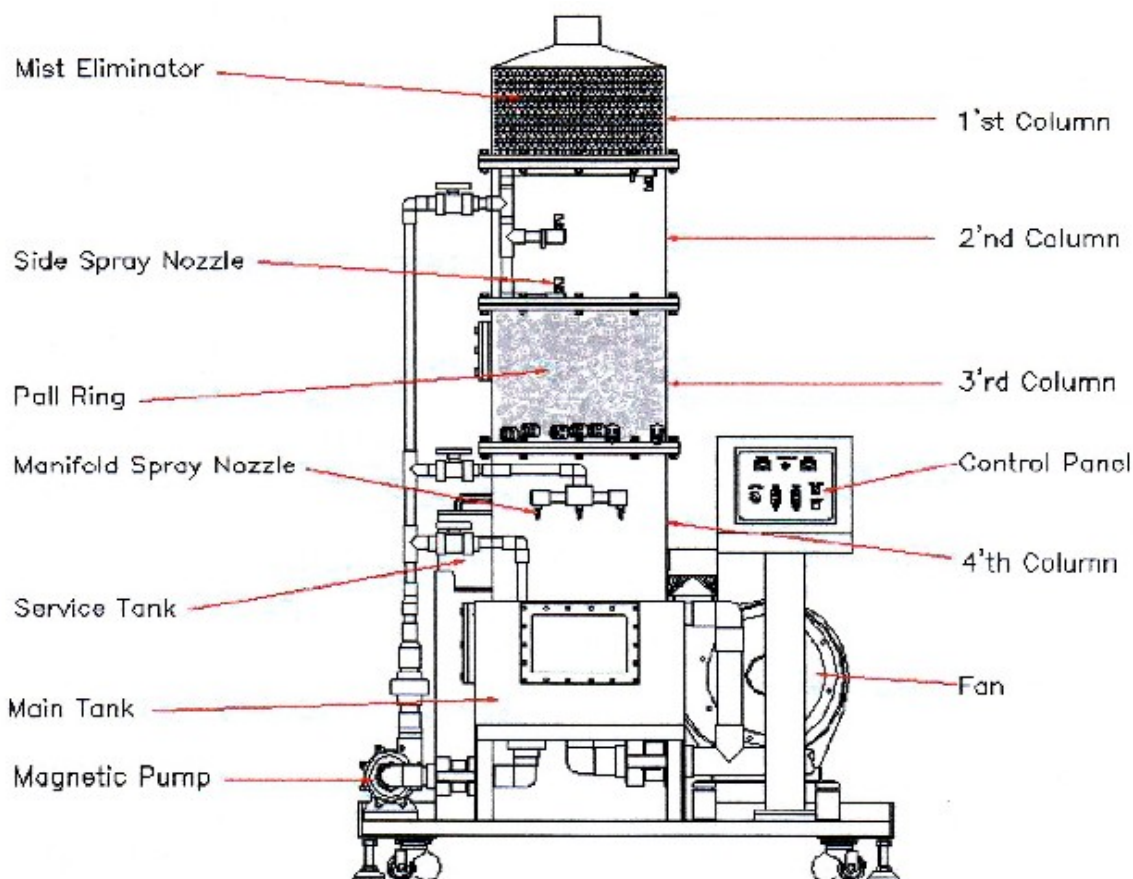


Figure 2.2: Wet Scrubber System for chlorine neutralization (SemiTel Corporation)

Chlorine and acid chlorides are removed from the gases as they pass through the curtain of droplets. The liquid is then drained back into the reservoir for continuous recirculation. Wet Scrubber alarm is operated when the main tank level is reduced below the low level sensor. At this time, the pump is stop but the blower still works for safety and preventing the pump from over-heat.

2.2.2 Vacuum Furnace

Furnace annealing is a process used in semiconductor device fabrication which consist of heating multiple semiconductor wafers in order to affect their electrical properties. Heat treatments are designed for different effects where wafers can be heated in order to activate dopants, change film to film or film to wafer substrate interfaces. Other effects are to densify deposited films, change states of grown films, repair damage from implants, move dopants or drive dopants from one film into another or from a film into the wafer substrate.

Furnace anneals may be integrated into other furnace processing steps, namely oxidations, or may be processed on their own. Furnace anneals are performed by an equipment that is especially built to heat semiconductor wafers. Furnaces are capable of processing lots of wafers at a time, but each process can last between several hours and a day.

In the fabrication of PLC, vacuum furnace (VF) is used to run annealing and consolidation process for deposited silica soot wafer. Vacuum furnace is a type of furnace that can heat materials typically metals, to very high temperatures and carry out processes such as brazing, sintering and heat treatment with high consistency and low contamination. [28]

In a vacuum-based furnace the absence of air or other gas prevent heat transfer within the product through convection and removes a source of contamination. Some of the benefits of a vacuum furnace are uniformity temperatures in the range of 2000–2800 °F or 1100–1500 °C and temperature can be controlled within a small area. For instance, quick cooling (quenching) of product and computerised process controlled to ensure

metallurgical repeatability. In fact, the furnace provides low contamination of the product by carbon, oxygen and other gases. Somehow, vacuum furnace removes the oxygen and prevent from rapid oxidation that caused by high temperatures.

An inert gas that is Argon, is typically used to quickly cool the treated metal back to non-metallurgical levels (below 400 °F) after the desired process in the furnace. This inert gas can be pressurized to 2 times or more than the atmospheric pressure and circulates through the hot zone area to pickup heat before passing through a heat exchanger to remove the heat. This process is repeated until the desired temperature is reached.

2.2.2.1 Chemical Reaction

Thermal oxidation of silicon is usually performed at a temperature between 800 and 1200°C. It may use either water vapour (steam) or molecular oxygen as the oxidant because it is consequently called as either wet or dry oxidation. The reaction can be either the oxidizing ambient may also contain several percent of hydrochloric acid (HCl) or the chlorine removes metal ions that may occur in the oxide.

Thermal oxide incorporates silicon consumed from the substrate and oxygen supplied from the ambient. Thus, it grows both down into the wafer and up out of it. For every unit thickness of silicon consumed, about two unit thicknesses of oxide will appear. Conversely, if a bare silicon surface is oxidized, 46% of the oxide thickness will lie below the original surface and 54% above it.

According to the commonly used Deal-Grove model, the time t required to grow an oxide of thickness X_o at a constant temperature on a bare silicon surface is:

$$t = \frac{X_0^2}{B} + \frac{X_0}{B/A} \quad (2.3)$$

where the constants A and B encapsulate the properties of the reaction and the oxide layer, respectively.

If a wafer that already contains oxide is placed in an oxidizing ambient, this equation must be modified by adding a corrective term τ , the time that would have been required to grow the pre-existing oxide under current conditions. This term may be found by using the equation for t above.

Solving the quadratic equation for X_0 yields:

$$X_0(t) = \frac{A}{2} \cdot \left[\sqrt{1 + \frac{4B}{A^2}(t + \tau)} - 1 \right] \quad (2.4)$$

2.2.2.2 Oxidation Technology

Most thermal oxidation is performed in furnaces, at temperatures between 800 and 1200°C. A single furnace accepts many wafers at the same time in a specially designed quartz rack which is called wafer boat. Historically, the boat entered the oxidation chamber from the side as this design is called horizontal boat and held the wafers vertically, beside each other. However, many modern designs hold the wafers horizontally, above and below each other, and load them into the oxidation chamber from below.

Vertical furnaces stand higher than horizontal furnaces, so they may not fit into some micro-fabrication facilities. However, it helps to prevent dust contamination.

Unlike horizontal furnaces in which falling dust can contaminate any wafer, vertical furnaces only allow it to fall on the top wafer in the boat.

For oxide quality, dry oxygen is preferred in thin oxide growing as it helps to produce smooth and fine oxide layer. On the other hand, wet oxygen is preferred to dry oxygen for growing thick oxides because of the higher growth rate. However, fast oxidation leaves more dangling bonds at the silicon interface, which produce quantum states for electrons and allow current to leak along the interface which is known as dirty interface. By the way, wet oxidation also yields a lower density oxide with lower dielectric strength.

The long time required to grow a thick oxide in dry oxygen makes this process impractical. Thick oxides are usually grown with a long wet oxidation bracketed by short dry ones (a dry-wet-dry cycle). The beginning and ending dry oxidations produce films of high-quality oxide at the outer and inner surfaces of the oxide layer, respectively.

Mobile metal ions can degrade performance of MOSFETs which sodium is the particular concern. However, chlorine can immobilize sodium by forming sodium chloride. Chlorine is often introduced by adding hydrogen chloride or trichloroethylene to the oxidizing medium. Its presence also increases the rate of oxidation.

Thermal oxidation can be performed on selected areas of a wafer, and blocked on others. Areas which are not to be oxidized are covered with a film of silicon nitride, which blocks diffusion of oxygen and water vapour. The nitride is removed after oxidation is complete. This process cannot produce sharp features because lateral (parallel to the surface) diffusion of oxidant molecules under the nitride mask causes the oxide to protrude into the masked area.

As impurities dissolve differently in silicon and oxide, a growing oxide will selectively take up or reject dopants. This redistribution is governed by the segregation coefficient, which determines how strongly the oxide absorbs or rejects the dopant and the diffusivity.

The orientation of the silicon crystal affects oxidation. From the Miller indices, $\langle 100 \rangle$ wafer oxidizes more slowly than a $\langle 111 \rangle$ wafer, but produces an electrically cleaner oxide interface. Thermal oxidation of any variety produces a higher-quality oxide with a much cleaner interface than chemical vapour deposition of oxide. However, the high temperatures that it requires restrict its usability. For instance in MOSFET processes, thermal oxidation is never been performed after the doping for the source and drain terminals are performed because it would disturb the placement of the dopants.

In vacuum furnaces the heat-treating process takes place inside an airtight vessel where a vacuum is created. This helps to alleviate surface reactions. Furnaces are built of several kinds of high temperature (refractory) materials to hold the process material and hold in the heat without breaking down during the months that they usually run.

Important specifications to consider when searching for vacuum furnaces include process temperature, height, width or tube outer diameter, length, and vacuum pressure range. The process temperature is the maximum temperature at which the unit may operate and still maintain rated performances. The height refers to the internal height dimension of the unit. The width refers to the internal width dimension of the unit or for tube furnaces, the outer diameter of the tube. The length refers to the length dimension of the unit or on tube furnaces, the heated length. The pressure range can be rough or in low

vacuum (760 to 25 torr), medium (25 to 10^{-3} torr), high vacuum (10^{-3} to 10^{-8} torr), ultra-high vacuum ($< 10^{-8}$ torr), and elevated pressures (> 760 torr).

Common configurations for vacuum furnaces include ashing, box or muffle, bottom loading, top loading, tube, bench or cabinet, continuous or conveying, and walk-in or truck-in. Ashing is also referred to as charring that is the step in a graphite furnace program that is designed to remove matrix constituents that might interfere with the measurement of the analyte. Box furnaces are convenient furnaces to use because as the name implies, the furnace has a box shape and a box-shaped interior. Bottom loading furnaces load the sample or product to be treated through the bottom of the chamber via a platform elevator. In a top loading furnace the product to be processed is loaded from the top. Cabinet or bench furnaces describe small batch equipments that are typically mounted on integral stands. Batch furnaces and ovens are typically suited for processing quantities of product in a single batch. A belt furnace has a continuous belt, carrying the unprocessed substrates through the furnace. In general, continuous or conveying conveyor units tend to be oriented toward automated production of greater quantities of small-to-medium-sized product. A pusher furnace is a type of continuous furnace in which the parts to be heated are periodically charged into the furnace in containers. These are pushed along the hearth against a line of previously charged containers, thus advancing the containers toward the discharge end of the furnace where they are used. Walk-in or truck-in furnaces describe larger size batch equipments, typically with double doors and integral carts, shelves, etc.

Common furnaces may have either a single set point or a programmable controller to adjust temperature stability. Choices for heat source such as arc,

combustion, electrical, conduction, induction, infrared, natural gas, propane, oil, microwave and steam. Common applications for vacuum ovens consist of aging, annealing, baking, brazing, soldering, burn-off, curing, drying, firing, sintering, foundry, melting, heat treating, hot pressing, preheating and quenching as well. Other features include over-temperature protection, three-zone or multi-zone, computer interface, application software, view ports, and service or entry holes.

2.2.3 DC Magnetron Sputter System

Sputter deposition, also known as physical vapour deposition (PVD) actually showed up soon after the invention of the light bulb as an unwanted light bulb filament material sputtering on the inside of the bulb. But as a vacuum deposition technology that has been in development since the late 1940's, it didn't really pick up popularity until the semiconductor industry adopted it as a metal technique for conductive trace paths between transistors sometime in the 1960's.

Sputtering became much better known in industry as the coating technique for applying the reflective layer on compact disc in the early 1980's. Since then it has slowly become a production method for consumer products with various applications. Sputter deposition requires a vacuum system with pumps, valves and gauges to evacuate the sputter chamber that holds the sputter cathode and the substrate coating stage. The sputter cathode is comprised of a magnet system located behind the target (the material to be sputtered) and a power feed from a DC power supply. As the correct vacuum pressure is achieved, argon gas is fed into the process chamber and ionized before accelerating

toward the target material. The argon ion strike the target with such force that it ejects a very small part of the target material outward. This is generally toward the substrate to deposit it upon the substrate surface.

Through the design of magnet assemblies and geometry, the sputter process has been optimized for the highest material transfer rate while attempting to coat the substrate uniformly. Despite this fact, sputter deposition is still somewhat random and requires that masks and shields be implemented to control where the deposition takes place. Also, in a typical arrangement where the target material is flat, the erosion of the target is not uniform. The target tends to erode the fastest areas of highest magnetic fields, creating grooves or channel in the target. When this groove depth approaches the target thickness, the target must be changed out. Typically, target utilization is not greater than 50%. However for precious metals, used target (as well as target material sputtered on shield and masks) may be recycled. Sputter yields a very fine coating that exhibits good adhesion and step coverage. One might liken it to a super fine spray that can spray metal instead of paint.

The sputtering process if applied correctly, produces a very fine metal layer on the surface of a plastic part. This coating which can be of nearly any metal or alloy, has good adhesion and exhibits good optical reflective quality on smooth molded parts.

In addition, sputtered coating can be quite cost effective that can add value to the parts being coated. Because sputter coating can often be applied in-line to the molding process, there is no penalty for cycle-time or parts throughput.

2.2.3.1 Literature of Sputter System

Direct Current Magnetron Sputter System that is known as DC Sputter system is a vacuum evaporation process which physically removes portions of a coating material that is called as the target. This system also deposits a thin, firmly bonded film onto an adjacent surface called the substrate. The process occurs by bombarding the surface of the sputtering target with gaseous ions under high voltage acceleration. As these ions collide with the target, atoms or occasionally entire molecules of the target material are ejected and propelled against the substrate, where they form a very tight bond. The resulting coating is held firmly to the surface by mechanical forces, although in some cases alloy or chemical bond may result.

Sputtering has proven to be a successful method of coating a variety of substrates with thin films of electrically conductive or non-conductive materials. One of the most striking characteristics of sputtering is its universality. Since the coating material is passed into the vapour phase by a mechanical rather than a chemical or thermal process, virtually any material can be deposited. Direct current is used to sputter conductive materials, while radio frequency is used for non-conductive materials.

Sputter deposition that is also known as physical vapour deposition (PVD) is a widely used technique for depositing thin metal layers on semiconductor wafers. These layers are used as diffusion barriers, adhesion or seed layers, primary conductors, antireflection coatings, and etch stops [29].

The range of sputtering application is large where one of the great importance include various thin films as demonstrated in table 2.1.

Table 2.1: Variety of thin films and material for sputtering application.

Application	Typical materials
Magnetic materials for data storage tapes	Co-Ni, Tb-Fe and Co-Ni-Cr
Optical materials for lens characteristics	CeO ₂ , MgO and MgF ₂
Lubricant materials for reducing friction	MoS ₂ , WS ₂ , and PTFE
Wear-resistant materials for lengthen cutting tool life	TiN, TiC, and ZrB ₂
Metallizing materials for microcircuits	Al, W-Ti, Al-Si and Al-Cu
Transparent conducting materials	xLn ₂ O ₃ -ySnO ₂
Thin-film resistors	Ni-Cr, Cr-Si and Cr- SiO
Amorphous bubble memory devices	Gd-Co. Lu ₃ Fe ₅ O ₁₂ , and Gd ₃ Ga ₅ O ₁₂
Microcircuit mask blanks	Cr

Other applications include oxide microcircuit insulation layers, amorphous optical films for integrated optics devices, piezoelectric transducers, photoconductors, luminescent films for display devices, optically addressed memory devices, video discs, solid electrolytes and thin film lasers.

2.2.3.2 Fundamental of Sputtering System

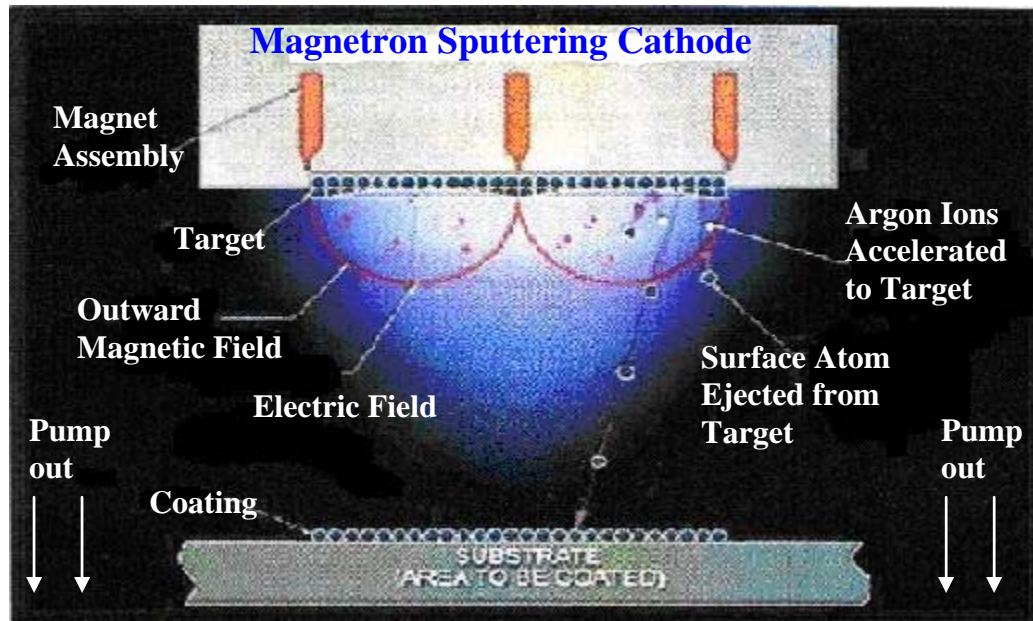


Figure 2.3: Sputtering phenomena of DC Magnetron Sputter System (Hanvac Corporation)

The primary use of DC Magnetron Sputter system is to sputter material from the target to the deposition surface. A magnetron sputter system consists of a plate of the material where all or part of the coating have magnets that are arranged behind it with alternating polarity. When power is supplied to the magnetron, a negative voltage of typically -300V or more is applied to the target.

This negative voltage attracts positive ions to the target surface at full speed. Generally when a positive ion collides with atoms at the surface of a solid, an energy transfer occurs. If the energy that is transferred to a lattice site is greater than the binding energy, primary recoil atoms can be created which can collide with other atoms and distribute their energy via collision cascades. A surface atom becomes sputtered if the energy that is transferred to it is about 3 times larger than the surface binding energy (approximately equal to the heat of sublimation).

When argon gas is fed into the chamber, the negative potential attracts argon ions to the target surface at full speed. When they collide with the surface, two important processes take place. Theoretically the atoms are knocked out of the target surface with mean kinetic energies of around 4 to 6 eV which is known as sputtering process. Secondly, secondary electrons are emitted from the target surface that are trapped by the magnetic fields and undergo further ionizing collisions sustaining the plasma. Also during the sputtering process a glow is observed as can be seen in figure 2.2. This is caused by excited ions relaxing to a lower energy state and emitting energy in the form of light. Different elements emit the visible light at a different wavelength and therefore a different colour will be observed. In this project, the noble gas especially argon is used to generate the plasma for sputtering process and a pale blue-violet light of argon plasma is observed at the process chamber. Argon is usually used for sputtering because of its inert nature and high purity.

Sputtering is the removal of atomized material from a solid due to energetic bombardment of its surface layers by ions or neutral particles. In general the sputtered atoms come off in approximately cosines distribution, where the angle is measured from the normal. Within the sputtering process gas ions out of plasma are accelerated towards a target consisting of the material to be deposited. Material is detached or sputtered from the target and afterwards it is deposited on a substrate in the vicinity. The process is realized in a closed recipient which is pumped down to a vacuum base pressure before deposition starts.

Prior to the sputtering procedure a vacuum of less than one tenth of a million of an atmospheric pressure must be achieved. From this point a closely controlled flow of

an inert gas such as argon is introduced. To enable the ignition of plasma usually argon is fed into the chamber up to certain pressure between 1 - 100 mTorr or around 1 -13 Pa. By natural cosmic radiation there are always some ionized argon ions available.

In the DC Sputtering, a negative potential up to some hundred volts is applied to the target. Sputtering of a target atom is just one of the possible results of ion bombardment of a surface. Aside from sputtering the second important process is the emission of secondary electrons from the target surface. These secondary electrons enable the glow discharge to be sustained. As a result, the argon ions are accelerated towards the target and set the material free where on the other hand they produce secondary electrons. These electrons cause a further ionization of the gas. The gas pressure p and the electrode distance d determine a break-through voltage U_D [31, 32] from which on a self sustaining glow discharge starts by following the equation $U_D = A \cdot pd/(\ln(pd) + B)$ with materials constants A and B . In general, the ionization probability rises with an increase in pressure and hence the number of ions and the conductivity of the gas simultaneously increase while the break through voltage drops. For a sufficient amount of ions and ionization rate, a stable burning plasma is produced and ready for sputtering the material.

To increase the ionization rate even further by emitting secondary electrons, a ring magnet below the target is used in the magnetron sputtering. The electrons in its field are trapped in cycloids and circulate over the targets surface. By the longer dwell time in the gas they cause a higher ionization probability and hence form a plasma ignition at pressures which can be up to one hundred times smaller than that for conventional sputtering. On the one hand, higher deposition rates can be realized thereby.

Beside, less collision occurs for the sputtered material on the way to the substrate because of the lower pressure and hence the kinetic energy at the impact on the substrate is higher. The electron density and hence the number of generated ions is the highest, where the B-field is parallel to the substrate surface. The highest sputter yield happens on the target area right below this region. An erosion zone is formed which follows the form of the magnetic field.

The induced plasma is effectively trapped between the magnetic and electric fields. This is only applied to the electrons which are magnetized as the Larmour radius is small compared to the plasma size. The ions on the other hand are unmagnetized as their Larmour radius is large compared to the plasma size. This requires a small range of magnetic fields strengths, usually on the order of 200 to 500 G. Smaller field strengths will result in too large of electron Larmour radii while larger field strengths will result in too small of ion Larmour radii.

During the sputter process a magnetic field can be used to trap secondary electrons close to the target. The electrons follow helical paths around the magnetic field lines, undergoing more ionizing collisions with neutral gaseous near the target than would otherwise occur. This enhances the ionization of the plasma near the target leading to a higher sputter rate. It also means that the plasma can be sustained at a lower pressure. The sputtered atoms are neutrally charged and so are unaffected by the magnetic trap.

The ions for the sputtering process are supplied by plasma that is induced in the sputtering equipment. In practice, a variety of techniques are used to modify the plasma properties especially ion density to achieve the optimum sputtering conditions. These

include the usage of RF (radio frequency) alternating current, utilization of magnetic fields, and application of a bias voltage to the target.

The bombardment of a non-conducting target with positive ions would lead to a charging of the surface and subsequently to a shielding of the electrical field. The ion current would die off. Therefore the DC sputtering is restricted to conducting materials like metals or doped semiconductors. There are two ways to produce dielectric films whereas the first is RF (radio frequency) sputtering which an ac-voltage is applied to the target. In second way, one phase ions are accelerated towards the target surface and sputter material to produce dielectric film.

The sputter process has almost no restrictions in the target materials, ranging from pure metals where a direct current (DC) power supply can be used to semiconductors and isolators which require a R.F. power supply or pulsed DC. Deposition can be carried out in either non reactive (inert gas only) or reactive (inert & reactive gas) discharges with single or multi-elemental targets. Alternatively, for reactive sputtering other gases like oxygen or nitrogen are fed into the sputter chamber additionally to the argon, to produce oxidic or nitridic films.

2.2.3.3 Theory of DC Magnetron Sputter System

The basic operation of the sputtering magnetron theory is Direct Current (DC) glow discharge. Sputtering magnetrons are characterized by a region with a strong electric field and a crossed (at perpendicular angle) magnetic field. There are two types of magnetron sputter system, the first is used to sputter material from a target and deposit the target material onto a substrate surface. This process is known as Physical Vapour

Deposition (PVD) and the second type of magnetron sputter system is used to produce high power microwave radiation (~ 1 GHz to 40 GHz) that is commonly found in microwave ovens. The only similarities between the two systems are the crossed E and B fields.

Sputtering is a purely physical process where atoms in a solid target material are ejected into the gas phase due to bombardment of the material by energetic ions. It is commonly used for thin-film deposition as well as analytical techniques.

Sputtering is largely driven by momentum exchange between ions and atoms in the material due to collisions. The process can be thought of as atomic billiards with the ion striking a large cluster of close-packed atoms. Although the first collision pushes atoms deeper into the cluster, subsequent collisions between the atoms can result in some of the atoms near the surface being ejected away from the cluster. The number of atoms ejected from the surface per incident ion is called the sputter yield and it is an important measure for the efficiency of the sputtering process. Other things that the sputter yield depends on are the energy of the incident ions, the masses of the ions and target atoms, and the binding energy of atoms in the solid.

The sputtered atoms that are ejected into the gas phase are not in their thermodynamic equilibrium state. They tend to condense back into the solid phase upon colliding with any surface in the sputtering chamber. This results in deposition of the sputtered material on all surfaces inside the chamber. This phenomenon is used extensively in the semiconductor industry to deposit thin films of various materials onto silicon, gallium arsenide (GaAs) or other wafers. It can also be used to apply thin coatings to glass for optical applications. It can be performed at very low temperatures

which makes it the ideal method to deposit thin film metal mask for PLC etching process. In fact, the use of sputtering to deposit thin films on a substrate is probably the most important application of sputtering today.

One important advantage of sputtering as a deposition technique is that the deposited films have the same composition as the source material. This might be surprising because as mentioned before the sputter yield depends on the atomic weight of the atoms to be sputtered. Therefore, one might expect one component of an alloy or mixture to sputter faster than other components, leading to a higher concentration of this component in the deposited film. The components are sputtered at different rates, however, since only surface atoms can be sputtered, the faster sputtering of one element leaves the surface enriched with another element. This effectively counteracts the difference in sputter rates that results in deposited films with the same composition as the target.

In fact, means free path and density are the key parameters in DC Sputter system to determine quality of sputter coating and the mechanism of the system. The ideal gas law is the equation of state for an ideal gas. The state of a gas is determined by its pressure p , volume V , and temperature T and the equation is given below:-

$$pV = nRT \quad \text{or} \quad pV = NkT \quad (2.5)$$

where n is the number of moles of gas, R is the gas constant, N is the number of particles together with Boltzmann constant, k . The unit for temperature is in kelvin or rankine.

DC glows are perhaps the simplest plasma discharge. It is likely that these discharges were the first low temperature plasma produced in a vacuum setting. Some of the early work on DC glow discharges was done by Michael Faraday from 1831 to 1851.

Theoretically, if an electron exists between the cathode and the anode without the plasma, it will be accelerated toward the anode. On average the electron will suffer a collision every mean free path. The mean free path is an inverse proportional to the effective cross sectional area for collision and multiplied by a number of particle per volume as given below

$$\lambda_{mfp} = \frac{1}{n\sigma} \quad (2.6)$$

Where σ is the cross section for all collision of the particles and n is the particle density which is the number of particles over the volume. Within this distance the electron will gain energy as demonstrated below

$$\varepsilon = \lambda_{mfp} (eE) \quad (2.7)$$

From the electric field equation,

$$E = \frac{V_{applied}}{d} \quad (2.8)$$

By substituting equation 2.8 into equation 2.7, it can be expressed as,

$$\varepsilon = \frac{e\lambda_{mfp} V_{applied}}{d} \quad (2.9)$$

By providing the electron gains more energy between collisions than it loses in the average collision, it will eventually have enough energy to ionize some of the local gas. This assumes that d and $V_{applied}$ are large enough. If an ionization event occurs, two electrons will travel toward the anode. This process can continue to occur, increasing the

number of electrons in an exponential fashion. When there is sufficient energy, this would produce an arc.

On the other hand, ions are drawn toward the cathode. While they might lose energy in collisions with the neutral gas particles, this general trajectory does not dramatically change. Upon hitting the cathode, providing that they have sufficient energy, some of the ions will cause the emission of secondary electrons. The exact number of electrons produced per incident ion is known as the secondary emission coefficient. In the range of energies typically observed in DC glows from between 100 to 1000 eV, secondary emission coefficient is approximately 0.1. Although this depends on energy, the higher the energy the higher secondary emission coefficient to be as well as the ion species and surface material/condition. Higher mass ions typically produce higher secondary emission coefficient, while the surface material/condition sets the work function for electron release and the lower the work function the higher the gain energy.

Basically, the characteristic of ion, electron and neutron are important to study the mechanism of the DC Sputter system. In order to master the technique of sputter coating, some theory and equation come into play. Commonly, density is proportional to mass over volume as presented below

$$\rho = \frac{m}{V} \quad (2.10)$$

The relations between pressures, mean free path, temperature, number of moles of gas and density are indicated as

$$p \propto \frac{1}{\lambda_{mfp}} \quad (2.11)$$

$$p \propto \rho \quad (2.12)$$

$$p \propto T \quad (2.13)$$

Thus,

$$p \propto \frac{n \cdot \rho \cdot T}{\lambda_{mfp}} \quad (2.14)$$

From the relation in equation 2.14, the content of the sputter coating process could be referred to study the effects of temperature, density and mean free path. In addition, uniformity and roughness of the coating surface are also included. Otherwise, the process condition in different parameters such as working pressure, gas flow rate, substrate temperature, current and voltage of the DC Sputter system which are based on the relation to conduct systematic and sophisticated experiments.

2.2.3.4 The DC Sputter Parameters

The resulting film properties can be controlled by adjusting the sputter parameters such as sputter current, working pressure, gas flow rate and substrate temperature.

The sputter current I_{sp} , determines mainly the rate of the deposition process and the time which remains for the arriving particles during the growth process. This can be either surface diffusion and agglomeration on existing growth centers or nucleation with other atoms. The applied voltage determines the maximum energy, with which sputtered particles can escape from the target (reduced by the binding energy). The applied voltage also determines the sputter yield, which is the number of sputtered particles per incoming ion.

The working pressure in the sputter chamber p , determines the mean free path λ for the sputtered material which is proportional to $1/p$. Together with the target substrate distance, the pressure controls how many collisions occur for the particles on their way from the target to the substrate. This can influence the porosity of the films as well as the crystallinity and texture [33, 34].

The argon gas flow rate is the parameter that keeps constant for every single process at certain flow rate that is set by mass flow controller (MFC).

The substrate temperature can have a strong impact on the growth behaviour with respect to the crystallinity or density of the samples. It can be adjusted between room temperature and up to 700 °C by adjusting the heater controller. But even during sputtering without external heating, the substrate temperature may rise considerably especially during long sputtering times for the deposition of thick films [35]. If the atoms are deposited with a low substrate temperature, the condensed atoms do not have enough kinetic energy and therefore high surface mobility allowed atoms jump across atomic steps and reach positions of a lower potential energy. A similar effect can also happen when high deposition rates are used. Atoms do not have enough time to find lower energy sites before being covered by other atoms. In this case, the temperature comes into density controlling issue.

In principle, a bias-voltage can be applied to the substrate up to ± 100 V which has the effect of accelerating electrons or ions towards the substrate or keeping them away. The directions of both accelerated electrons and ions may have an influence on the layer growth [36, 37].

2.2.3.5 DC Sputter for Chromium Coating

A magnetron sputter gun is used to apply high voltages for up to 1 kV and maximum power of 2 kW to the target. The films were produced in constant current mode where constant power and constant voltage modes are also available.

A potential of several hundred volts is applied at the cathode. Plasma or glow discharge is formed by passing a current at 100 V to several kV through a gas, usually argon or another noble gas. A small population of atoms within the cell is initially ionized through random processes. The base pressure of the chamber is evacuated by Turbo Molecular Pump (TMP) to a lower base pressure of 10^{-6} Torr, while argon gas is fed into the chamber for argon plasma induced purpose. Mass flow controllers (MFC) is used to regulate gas flow of argon gas and pressure during deposition to keep constant of the argon flow, the process chamber pressure is maintained at defined pressure by Automatic Pressure Controller (APC). The argon gas flow is set at 5 sccm by default and APC is work with determined throttle valve position to enables pressure controlling. Then, plasma discharge is induced by a direct current (DC) power supply at a constant current mode, when the chamber is filled with argon gas at a given pressure and circularly shaped plasma is formed adjacent to the cathode (metal target) surface. The target used in this study is high purity chromium target for metal masking.

The ions (which are positively charged) are driven towards the cathode by the electrical potential, and the electrons are driven towards the substrate at the same potential. The initial population of ions and electrons collide with other atoms, thus

ionizing them. As long as the potential and gas flow maintained, a population of ions and electrons remains.

Some of the ions kinetic energy is transferred to the cathode. This happens partially through the ions that strike the cathode directly. The primary mechanism, however, is less direct. Ions strike the more numerous neutral gas atoms, transferring a portion of their energy to them. These neutral atoms then strike the cathode. Whatever elements that strike the cathode, collisions within the cathode redistribute this energy until a portion of the cathode is ejected typically in the form of free atoms. This process is known as sputtering. Once free of the cathode, atoms move into the bulk of the glow discharge through drifting and due to the energy that they gained from sputtering. The atoms can then be collisionally excited. These collisions may be with ions, electrons, or other atoms that have been previously excited by collisions with ions, electrons, or atoms. Once excited, atoms will lose their energy fairly quickly. One of the various ways that this energy can be lost is importantly radiative, indicating that a photon is released to carry the energy away.

The energy that is supplied to the surface of a growing film is an important parameter that together with the substrate temperature determine film density, uniformity, microstructure and properties. There are several processes in plasma that contribute to the energy input introduced into the surface layers. The main bombarding scheme of importance in the case of magnetron sources are sputtering gas ions and energetic neutral atoms including reflected neutrals from the cathode surface and sputtered atoms.

The chromium target to be deposited is bombarded by energetic ions which will dislodge atoms of the chromium target. The dislodged atoms will have substantial kinetic energies and some will fly to the substrate to be coated and stick there.

Since the target electrode is always the cathode that is negatively charged, it will attract the argon ions (Ar^+) and thus, it is bombarded by a constant flux of relatively energetic argon ions. The ions that are necessary for the bombardment of the target are simply extracted from the argon plasma that burns between the target and the substrate. This ion bombardment will liberate atoms from the chromium target in all directions.

Some chromium atoms will reach the substrate to be coated, others will miss it and some will become ionized and return to the target. The important point for the atoms that reach the substrate is that the energy is large enough to allow the chromium atoms to stick at the substrate surface, but not so large to liberate the substrate atoms. Therefore, sputtered layers usually stick well to the substrate.

2.2.4 Spin Coater

A spin coater is designed with precise and consistent stepper motor together with the program control circuit which enables multi range setting for the spin coating process. This component is used for thin film photoresist coating in PLC fabrication process. It is required to be placed on a solid and level surface, especially the chuck is leveled for optimum performance. It should also be free from vibration and extreme temperature. Vacuum is required for the machine to operate and it is applied at the chuck to hold the wafer sample while spinning at high RPM.

Proper centering is done manually, but the use of templates and measurements can aid in this operation. Furthermore, purge N₂ is required as a safety factor to fill the interior of the unit with inert N₂ and by excluding dangerous gasses. Somehow, the cycle will not start if the spin coater's door is not closed properly as to prevent the wafer from spinning off the coater chamber.

The spin coater is programmed with four parameters that comprise of acceleration time, spin time, spin speed and deceleration time setting to enter the recipe and start the spin coating process. The specification of the spin coater is shown in table 2.2.

Table 2.2: Spin coater specification

Speed	0 – 9999 RPM
Acceleration/ Deceleration	<1 – 25.5 seconds (in 0.1 sec. increments)
Dwell (Spin Time) each step	Up to 999 seconds (in 1.0 sec. increments)
Dimensions	Depth 15.4” (39.4 cm) Width 12.0” (30.56cm) Height 10.5” (26.7cm)
Weight	32 Lbs (14.5 kg)
Power Input	115/230 VAC, 1Phase, 300VA
Vacuum Input	430 to 635mmHg (17” to 25” Hg)
Purge Input	0.55 cfm – at 2 psi N ₂ , 5 psi maximum (external) OR 2.2 cfm @ 60 to 80 psi (internal)

For PR application, the wafer is covered with PR by spin coating. A viscous, liquid solution of photoresist is dispensed onto the wafer, and the wafer is spun rapidly to produce a uniformly thick layer. The spin coating typically runs at 4000 to 8000 rpm for 30 to 60 seconds, and it produces a layer between 2.5 and 0.5 microns thick.

2.2.5 Hot Plate and Oven

Hot plate and oven are used to heat or dry the wafer at certain constant and stable temperature. The temperature range can be set from 0 to several hundred degree Celcius. Hot plate and oven are used in PLC fabrication for dehydrating and baking in lithography process.

Commonly, there are three modes of baking processes that include soft-bake, post-exposure bake and hard-bake that use hotplate or oven in lithography process. The photoresist-coated wafer is soft-baked or prebaked in hotplate or oven to drive off excess solvent, typically at 90 to 110 °C for 2 to 5 minutes. A post-exposure bake is performed before developing at around 110 °C for a few minutes. This is typically to help reduce standing wave phenomena that are caused by the destructive and constructive interference patterns of the incident light. The resulting wafer is then hard-baked, typically at 100 to 130 °C for 10 to 30 minutes. The hard-bake solidifies the remaining photoresist, to make a more durable protecting layer in future ion implantation, wet chemical etching, or plasma etching.

2.2.6 Photomask and Mask Aligner

For PLC fabrication, two types of Photomask namely Beam Splitter and Array Waveguide Grating (AWG) are studied in this project for passive PLC device. A Photomask is an opaque plate with holes or transparencies that allow light to shine through it in a defined pattern which is commonly used in photolithography.

Lithographic photomasks are typically transparent fused silica blanks that are covered with a pattern which is defined with a chrome metal absorbing film. Photomasks are used at wavelengths of 365 nm, 248 nm, and 193 nm. These plates have also been developed for other forms of radiation sources such as 157 nm, 13.5 nm Extreme Ultraviolet (EUV), X-ray, electrons and ions, but these require entirely new materials for the substrate and the pattern film.

A beam of electrons is used to expose the pattern that is defined in photomask and it travels over the surface of the substrate in either a vector or raster scan manner. When the photoresist on the mask is exposed, the chrome can be etched away to leave a clear path for the light in the stepper/scanner systems to travel through. The mask aligner consists of alignment stage, optical system, UV light source, vacuum holders for wafer and mask, microscope with alignment stage, CCD camera, main controller and UV lamp power supplier.

Four exposure modes such as soft contact, hard contact, vacuum contact and proximity are available for the mask aligner system with manually controller. The optical system with UV lamp at the wavelength range from 365nm to 436nm enables g-line (436nm), h-line (405nm) and i-line (365 nm) modes. The sub-micron alignment is staged together with microscope and CCD camera for precise alignment and inspection. Automatic exposure timer ranges from 0 to 999 second with every 0.1 second increment. Two modes of UV lamp controller that comprise of Constant Power (CP) and Constant Intensity (CI) are employed to tune the UV light source power or intensity for lithography process.

The vibration free table, ventilation and cooling system are required for the mask aligner to operate in optimum condition. Furthermore, dust free yellow room and temperature together with humidity controlling system are also critical for lithography process. Temperature of the yellow room should be set between 20 °C to 23 °C and relative humidity should be around 45 % to 55 %. Additionally, pneumatics such as nitrogen, vacuum and compressed air are included as well.

2.2.7 ICP Etching System

Inductively Coupled Plasma (ICP) Etching System plays an important role in material processing for semiconductor and photonics. ICP etching system is also known as Inductively Coupled Plasma Reactive Ion Etch (ICP RIE). ICP is a type of plasma source in which the energy is supplied by electrical currents which are produced by electromagnetic induction, especially by time-varying magnetic fields. There are two types of ICP geometries that are planar and cylindrical. In planar geometry, the electrode is a coil of flat metal wound like a spiral and in cylindrical geometry, it is like a helical spring.

When a time-varying electric current is passed through the coil, it creates a time varying magnetic field around it. This in turn induces azimuthally electric currents in the rarefied gas that lead to breaking down and formation of plasma.

ICP is an important tool for semiconductor and photonics material processing, particularly to manufacture critical features. ICP discharges are of relatively high electron

density, up to the order of 10^{11} - 10^{12} cm³. As a result, ICP discharges have wide applications where high density plasma is necessary.

ICP etching system is an evolution essence from Capacitively Coupled Plasma that is known as CCP etching system. The benefit of ICP discharges is that they are relatively free of contamination because the electrodes are completely outside the reaction chamber. In contrast, in capacitively coupled plasma (CCP) the electrodes are placed inside the reactor and are thus exposed to the plasma and subsequent reactive chemical species.

ICP RIE of silica etching is a modified Bosch process where the hybrid of passivation is in parallel with the etching process. ICP RIE is an etching technology that is implemented in microfabrication for highly anisotropic etch. It uses chemically reactive plasma and physical sputtering to remove material that is deposited on wafers which enables in single directional etch. The plasma is generated under low pressure (vacuum) by an electromagnetic field. High-energy ions from the plasma attack the wafer surface and react with it.

A typical (parallel plate) RIE system consists of a cylindrical vacuum chamber, with a wafer platter situated in the bottom portion of the chamber. The wafer platter which is usually grounded, is electrically isolated from the rest of the chamber. Gas enters through small inlets in the top of the chamber, and exits to the vacuum pump system through the bottom. The types and amount of gas used vary depending upon the etch process; for instance sulphur hexafluoride and tetrafluoromethane are commonly used for etching silicon and silica respectively. Gas pressure is typically maintained in a

range between a few milli-torr and a few hundred milli-torr by adjusting gas flow rates and/or adjusting an exhaust orifice.

Other types of RIE systems exist, including inductively coupled plasma (ICP) RIE. In this type of system, the plasma is generated with an RF powered magnetic field. Very high plasma densities can be achieved, though etch profiles tend to be more isotropic.

A combination of parallel plate and inductively coupled plasma RIE is possible. In this system, the ICP is employed as a high density source of ions which increases the etch rate, whereas a separate RF bias is applied to the substrate (silicon wafer) to create directional electric fields near the substrate to achieve more anisotropic etch profiles.

A plasma is initiated in the system by applying a strong RF (radio frequency) electromagnetic field to the wafer platter. The field is typically set to a frequency of 13.56 megahertz at a few hundred watts. The oscillating electric field ionizes the gas molecules by stripping them of electrons to create plasma.

In each cycle of the field, the electrons are electrically accelerated up and down in the chamber, sometimes striking both the upper wall of the chamber and the wafer platter. At the same time, the much more massive ions move relatively a little in response to the RF electric field. When electrons are absorbed into the chamber walls, they are simply fed out to ground and do not alter the electronic state of the system. However, electrons that are absorbed into the wafer platter cause the platter to build up charge due to its DC isolation. This charge build up develops a large negative voltage on the platter, typically around a few hundred volts. The plasma itself develops a slightly positive charge due to the higher concentration of positive ions compared to the free electrons.

Because of the large voltage difference, positive ions tend to drift toward the wafer platter where they collide with the samples to be etched. The ions react chemically with the materials on the surface of the samples, but can also knock off (sputter) some materials by transferring some of their kinetic energy. Due to the mostly vertical delivery of reactive ions, reactive ion etching can produce anisotropic etch profiles which contrast with the typically isotropic profiles of wet chemical etching.

Etch conditions in an RIE system depend strongly on the many process parameters such as pressure, gas flows, and RF power. A modified version of RIE is deep reactive-ion etching that is used to excavate deep features.

Furthermore, ICP System consists of Turbo Pump, Rotary Pump, Gauges (Baratron Gauge, Pirani Gauge and Ion Gauge), and Auto Pressure Controller (APC) for vacuum processing requirement. RF source power generator system includes radio frequency power supply, automatic matching network and matching network controller for plasma generating in etching process. Piping lines for several gases are fed into the process chamber for plasma processing.

2.2.7.1 Dry Scrubber

A Dry Scrubber system is similar to the Wet Scrubber system that works as an important supplementary component. It is designed to filter greenhouse gases such as nitrous oxide, sulphur hexafluoride, fluorocarbon, hydrofluorocarbons, perfluorocarbons and chlorofluorocarbons type of gases that contribute to the greenhouse effect.

This apparatus composes of unique gas flow and electrical control scheme. It offers a safe, efficient and reliable solution for treatment of toxic and harmful gases from

semiconductor related industries. In addition, it is also unique, simple in design and constructed for ease of use and maximum process safety.

Several exclusive features in this machine include outlet concentrations that are less than Threshold Limit Values (TLV), operation in normal pressure and room temperature, no energy consumption for abatement of waste gas and cost efficiency. Other specifications are automatic bypass system, small foot-print and clean room compatibility, nitrogen purge as prevention for exposure to harmful gases, canister support and fixing belt for safety purposes.

The essential component of the dry scrubber system is the ZEBENT reactive absorbent. The pellet-type material is specifically developed to chemically and irreversibly bind the process gases. The ZEBENT waste gas treatment system removes hazardous process gases on the basis of chemical reaction (chemisorption) to stabilise salts at ambient temperature. No external heating, moisturization or other facilities are required for the gas treatment. The type and quality of ZEBENT is specified according to the appropriate treatment. The canisters that are charged with ZEBENT are the gas treating parts of the system. The canisters essentially equip the foot-master with wheels for ease of movement and anchoring units to firm fixation.

The dry scrubber system consists of air-actuating automatic valve and the automatic ball with completely isolated with the process gas line as to prevent corrosion-problem and to ensure operational safety free from electrical error.

Sampling ports are provided at the inlet and outlet of the system to enable analysis of the untreated and treated gases. For keeping the Threshold Limit Values (TLV) limitation, canister will be exchanged after its life time or break-through of

ZEBENT. Arrangements should be made at this time with the supplier/agent for changing and maintenance of the used-up canister.

2.2.7.2 Vacuum System

Vacuum system plays an important role in plasma technology. It is required in plasma processing system such as ICP etching system, DC Sputter system, ion beam deposition system, electron beam deposition system and etc. The Vacuum system in ICP etching system consists of a rotary pump as the primary pump and a Turbo Molecular Pump (TMP) as the secondary pump. The Rotary pump can attain pressures as low as 10^{-3} Torr and the TMP which can generate many degrees of vacuum from intermediate vacuum ($\sim 10^{-5}$ Torr) up to ultra-high vacuum levels ($\sim 10^{-11}$ Torr). Typically, the TMP is connected to a rotary pump as a backing pump which produces a pressure that is low enough for the TMP to work efficiently. Automatic Pressure Controller (APC) is used to control the throttle valve to attain preset chamber pressure for etching process.

2.2.7.3 Radio Frequency Power Generator System

Radio Frequency (RF) Power Generator System consists of radio frequency power supply, automatic matching network and matching network controller. The SEREN R1001 and R301 RF Power Supply are used as ICP Power and Bias Power respectively. Both of the ICP and Bias RF Power Supply provide 13.56 MHz, level-controlled radio frequency power outputs that are up to 1000 Watts and 300 Watts respectively. The RF Power Supply features forward and reflected RF Power display, Control Mode, Power Supply Status and RF or DC Probe Voltage. Other features like

forward power, Load Power Leveling and programmable pulsing are also included. RF Power Supply consists of three levelling modes which are Forward Power Leveling mode, Voltage Leveling mode and Load Power Leveling mode.

Both ICP and Bias RF Power Supply are used in conjunction with connection to Automatic Matching Network and MC-2 Matching Network Controller. AT-10 Automatic Matching Network and AT-3 Automatic Matching Network are used in ICP and Bias RF Power Generator System respectively. Both AT-10 and AT-3 Automatic Matching Network consist of two variable capacitors and a single fixed inductor but feature for 1000 W and 300 W nominal input powers respectively. The matching network circuit topology is an “L” type circuit which the configuration provides a wide tuning range and low insertion loss and it delivers maximum power transfer to the plasma load. The variable capacitors within Automatic Matching Network are driven by servo-motors which are powered by SEREN MC-2 Matching Network Controller. The schematic of RF Power Generator System configuration is illustrated in figure 2.4.

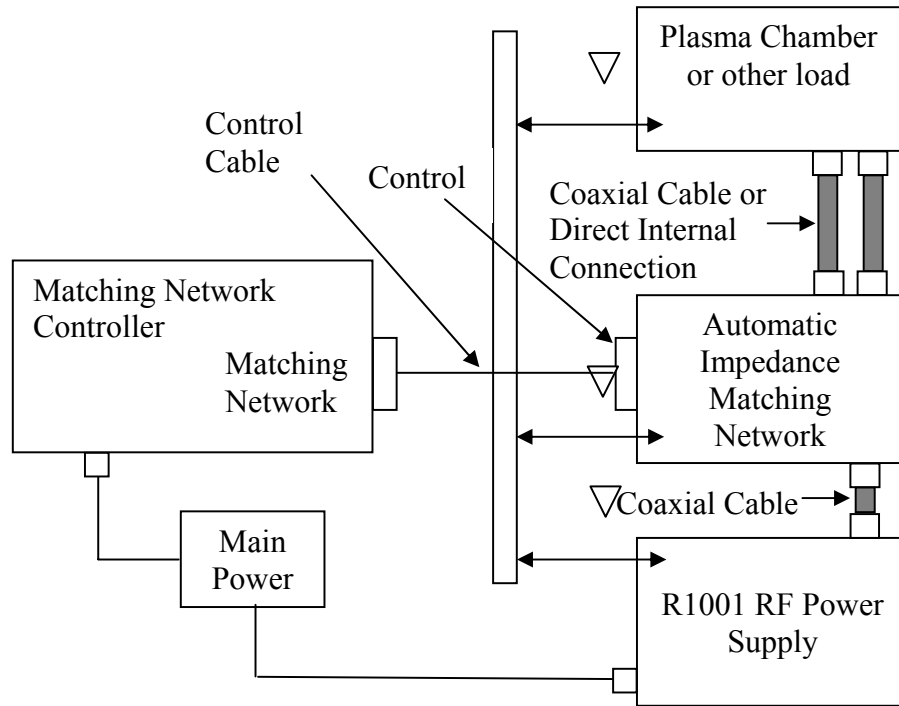


Figure 2.4: Schematic of RF Power Generator System

2.2.7.4 Processing Gases

Tetrafluoromethane (CF_4), Hexafluoroethane (C_2F_6), Oxygen (O_2), Hydrogen (H_2), Argon (Ar) and Nitrogen (N_2) are processing gases that are connected to the process chamber where their flow of rate is controlled by Mass Flow Controller (MFC). A standard steel piping line feeds appropriate gas or mixture gases into the process chamber for ashing, etching or cleaning process.

2.2.8 Wet Bench and Fume Hood

A fume hood that is also known as a fume cupboard is designed to limit a person's exposure to hazardous fumes. It was originally manufactured from timber, but now epoxy coated mild steel is the main construction material. Two main types of this unit exist, namely ducted and recirculation. With the ducted type, old asbestos vent pipe has been superseded on health grounds, typically with PVC or polypropylene. The principle is the same for all units where the air is drawn in from the front of the cabinet by a fan and expelled either outside the building or purified through filtration before being fed back into the room.

The Fume hood can accommodate one to three operators. The front is a movable sash, usually in a glass that is able to move up and down on a counterbalance mechanism. On educational versions, the sides of the unit are often glass that allows several pupils to gather around a fume hood at once.

Most fume hoods for industrial purposes are ducted-based. In this unit, the air is removed from the workspace and dispersed into the atmosphere. Additional features include compressed air port, deionized (DI) water and yellow light for photolithography and wet bench processing compatibility. These features enable safety wet bench or bench chemistry processes such as cleaning, spin coating, wet etching, photoresist processing and etc.

2.2.9 Prism Coupler

Prism coupler instruments are used to measure the refractive index or birefringence and thickness of dielectric and polymer films. Since refractive indices of a material depend upon the wavelength of the electromagnetic radiation transmitted, a monochromatic laser is used in conjunction with a prism of known refractive index. The laser beam is directed through a side of the prism, it is bent and normally reflected back in the opposite side into a photo detector. However, at certain values of the incident angle θ , the beam does not reflect back, but instead it is transmitted through the base into the film sample. These angles are called mode angles. A computer-driven rotary table varies the incident angle of the laser. The first mode angle estimated, determines the refractive index and the angle difference from one mode to the next that represents the sample thickness. The prism coupler is capable to measure bulk, single, double and super thin layer structure.

In PLC fabrication, prism coupler is an important measurement tool which is used to inspect the thickness and refractive index of the silica layer after being consolidated from the vacuum furnace. The Prism coupler is a very important tool to assist in silica deposition recipe controlling and analysis.

2.2.10 Surface Profiler

Surface profiler or stylus profilometry is an electronic-based machine to measure the deflection of a stylus that is scanned over the surface to be characterized.

The stylus measurement gives reliable results on all hard surfaces, particularly on transparent thin films since it is based on physical contact. This instrument can also give some information about the roughness of horizontal and moderately sloped surfaces, but no information can be obtained about surfaces that are steeper than the tip angle.

The horizontal resolution of a profilometry measurement is around 2 μm , limited by the table movement accuracy and the tip curvature. The vertical resolution is limited by vibrations from the surroundings and the sensitivity of the electronic measurement system, and this is typically around 2 - 10 nm.

On most stylus profiler systems, the user can pre-program a sequence of measurements on specified locations and thus automate measurements across an entire wafer. Simple analysis of the measured topographies, as for instance step height measurements can also be included in the sequence. When it comes to characterizing high aspect ratio structures, the stylus profilometry technique is limited by the tip angle and the radius of curvature of the stylus. They are typically around 60 degrees and 5-10 μm , respectively as manifested in Figure 2.1. Therefore, the stylus can not be used to measure aspect ratios much larger than 1:1. The newest tools from Tencor Surface Profiler feature a so-called "dipping mode", in which a very thin and long stylus is lowered onto the sample at every measurement point.

Surface Profiler has 3 types of sensors with ranges of 20 μm , 400 μm , and 2 mm, respectively. The surface profiler incorporates profiling technology, high magnification image displays and digital data handling for profiling both thin and thick films. It also provides routine measurements of step heights less than 200 Å. The Alpha-Step 200 can identify discontinuities in the tens of Angstroms. The surface profiler

central processing unit (CPU) automatically controls levelling and measurement. The monitor displays both the actual scan, via the high-power video microscope, and the graphic charts of the scan profile. The adjustable stylus force which ranges from 1 to 25 mg consists of maximum sample dimensions of 16.5 mm thickness and 162 mm diameter.

2.2.11 Frame Capture Microscope System

The microscope is used in conjunction with capture card, CCD camera, monitor and computer. The frame capture microscope system enables photo capturing to magnify surface and cross sectional inspection of the diced sample. Microscope makes sample inspection easy and instant to check the sample result. The schematic of frame capture microscope is demonstrated in figure 2.5. The detail of the capture system and setup will be presented in chapter 4.

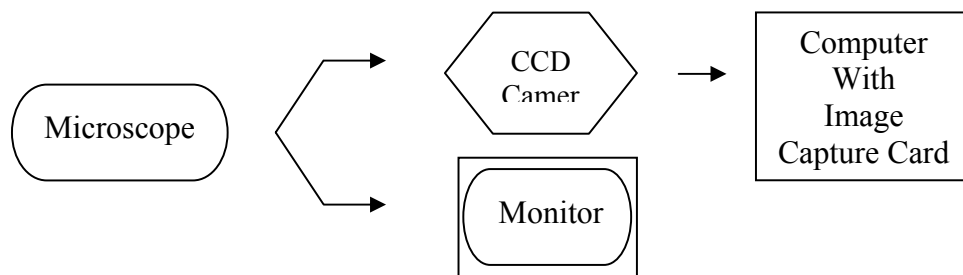


Figure 2.5: Schematic of frame capture microscope system

2.2.12 Scanning Electron Microscopy

The scanning electron microscope (SEM) is a type of electron microscope that is capable of producing high-resolution images of a sample surface. Due to the manner in which the image is created, SEM images have a characteristic of three-dimensional appearance and these are useful for judging the surface structure of the sample.

In a typical SEM, electrons are thermionically emitted from a tungsten or lanthanum hexaboride (LaB₆) cathode and they are accelerated towards an anode. Alternatively, electrons can also be emitted via field emission (FE). Tungsten is used because it has the highest melting point and the lowest vapour pressure of all metals, thereby allowing it to be heated for electron emission. The electron beam, which typically has an energy ranging from a few hundred eV to 100 keV is focused by one or two condenser lenses into a beam with a very fine focal spot size of 1 nm to 5 nm. The beam passes through pairs of scanning coils in the objective lens which deflect the beam horizontally and vertically, so that it scans in a raster fashion over a rectangular area of the sample surface. When the primary electron beam interacts with the sample, the electrons lose energy by repeated scattering and absorption within a teardrop-shaped volume of the specimen. This specimen is known as the interaction volume which extends from less than 100 nm to around 5 μm into the surface. The size of the interaction volume depends on the beam accelerating voltage, the atomic number of the specimen and the specimen's density. The energy exchange between the electron beam

and the sample results in the emission of electrons and electromagnetic radiation which can be detected to produce an image as described below.

The most common imaging mode monitors low energy (<50 eV) secondary electrons. Due to their low energy, these electrons originate within a few nanometers from the surface. The electrons are detected by a scintillator-photomultiplier device and the resulting signal is rendered into a two-dimensional intensity distribution that can be viewed and saved as a Digital image. This process relies on a raster-scanned primary beam. The brightness of the signal depends on the number of secondary electrons reaching the detector. If the beam enters the sample perpendicular to the surface, then the activated region is uniform for about the axis of the beam and a certain number of electrons "escape" from within the sample. As the angle of incidence increases, the "escape" distance of one side of the beam will decrease and more secondary electrons will be emitted. Thus, steep surfaces and edges tend to be brighter than flat surfaces which results in images with a well-defined, three-dimensional appearance. Using this technique, resolutions less than 1 nm are possible.

Backscattered electrons (BSE) consist of high-energy electrons originating in the electron beam that are reflected or back-scattered out of the specimen interaction volume. BSE may be used to detect contrast between areas with different chemical compositions, especially when the average atomic number of the various regions is different. This is possible since the brightness of the BSE image tends to increase with the atomic number. Another benefit of backscattered electrons is to form an electron backscatter diffraction (EBSD) image that is feasible to determine the crystallographic structure of the specimen. There are fewer backscattered electrons that are emitted from a sample than

secondary electrons. The number of backscattered electrons leaving the sample surface upward might be significantly lower than those that follow trajectories toward the sides. Additionally, in contrast with the case of secondary electrons, the collective efficiency of backscattered electrons cannot be significantly improved by a positive bias that is common on Everhart-Thornley detectors. This detector that is positioned on one side of the sample has low collective efficiency for backscattered electrons due to small acceptance angles. In a "doughnut" type arrangement, a dedicated backscattered electron detector is placed above the sample where the electron beam passing through the hole of the doughnut. This greatly increases the solid angle of collection and allows for the detection of more backscattered electrons.

On the other hand in cathodoluminescence (CL), the emission of light for atoms that are excited by the high-energy electrons before returning to their ground state is analogous to the UV-induced fluorescence. Some materials such as zinc sulphide and fluorescent dyes exhibit both phenomena. Cathodoluminescence is most commonly experienced in everyday life as manifested by the light emission from the cathode ray tube in television sets and computer CRT monitors. In the SEM, CL detectors can either collect all light that is emitted by the specimen or analyze the wavelengths emitted by the specimen. Another benefit of the detectors is to display a spectrum or an image of the cathodoluminescence in real colour.

The spatial resolution of the SEM depends on the size of the electron spot that in turn depends on the magnetic electron-optical system which produces the scanning beam. The resolution is also limited by the size of the interaction volume or the extent to which the material interacts with the electron beam. The spot size and the interaction volume

are both very large compared to the distances between atoms. As a consequence, the resolution of the SEM is not high enough to image down to the atomic scale as it is possible in the transmission electron microscope (TEM). The SEM has compensating advantages including the ability to image a comparatively large area of the specimen, the ability to image bulk materials (not just thin films or foils), and the variety of analytical modes available for measuring the composition and the nature of the specimen. Depending on the instrument, the resolution can fall somewhere between less than 1 nm and 20 nm. In general, SEM images are much easier to interpret than TEM images.

Conventional SEM requires samples to be imaged under vacuum which indicates that these samples would produce a significant amount of vapour. For instance in biological samples, they need to be either dried or cryogenically frozen. As a result, processes involving transitions to or from liquids or gases such as the drying of adhesives or melting of alloys could not be observed.

Scanning electron microscopy (SEM) is a very powerful characterization technique that is used in many fields of science. It is based on detection of electrons that are emitted from a sample under bombardment with high energy electrons. SEM is normally limited to conductive samples, since non-conductive samples will charge up under electron bombardment and deflect the high-energy electrons directly towards the detector.

Being photo-realistic, SEM analysis gives excellent information about the surface morphology and by using energy dispersive x-ray spectroscopy, quantitative chemical composition data can also be obtained. Practically, the smallest details can be discerned with the SEM method in nanometer region.

2.2.13 Energy Dispersive X-ray

Energy Dispersive X-ray (EDX) is implemented in conjunction with SEM and it is not a surface science technique. An electron beam strikes the surface of a conducting sample. The energy of the beam is typically in the range of 10-20keV. This causes X-rays to be emitted from the point of the material. The energy of the emitting X-rays depends on the material under examination. The X-rays are generated in a region of about 2 microns in depth that explains why EDX is not a surface science technique. By moving the electron beam across the material, an image of each element in the sample can be acquired in a manner similar to Scanning Acoustic Microscope (SAM). Due to the low X-ray intensity, images usually take a number of hours to acquire. Elements of low atomic number are difficult to detect by EDX. The Lithium drifted Silicon (SiLi) detector is often protected by a Beryllium window. The absorption of the soft X-rays by the Be precludes the detection of the elements below an atomic number of 11 (Na). In windowless systems, elements with atomic number as low as 4 (Be) have been detected, but the problems involved get progressively worse as the atomic number is reduced.

The detector used in EDX is the Lithium drifted Silicon detector. This detector must be operated at liquid nitrogen temperatures. When an X-ray strikes the detector, it will generate a photoelectron within the body of the silicon (Si). As this photoelectron travels through the Si, it generates electron-hole pairs. The electrons and holes are attracted to opposite ends of the detector with the aid of a strong electric field. The size of the current generating pulse depends on the number of electron-hole pairs created which

in turn depends on the energy of the incoming X-ray. Thus, an X-ray spectrum can be acquired by giving information on the elemental composition of the material under examination.

Recently, an exciting development in the field of EDX is the X-ray microcalorimeter. This device has a much higher energy resolution ($\sim 3\text{eV}$) than the traditional Si (Li) detector.

2.3 Fabrication Environment

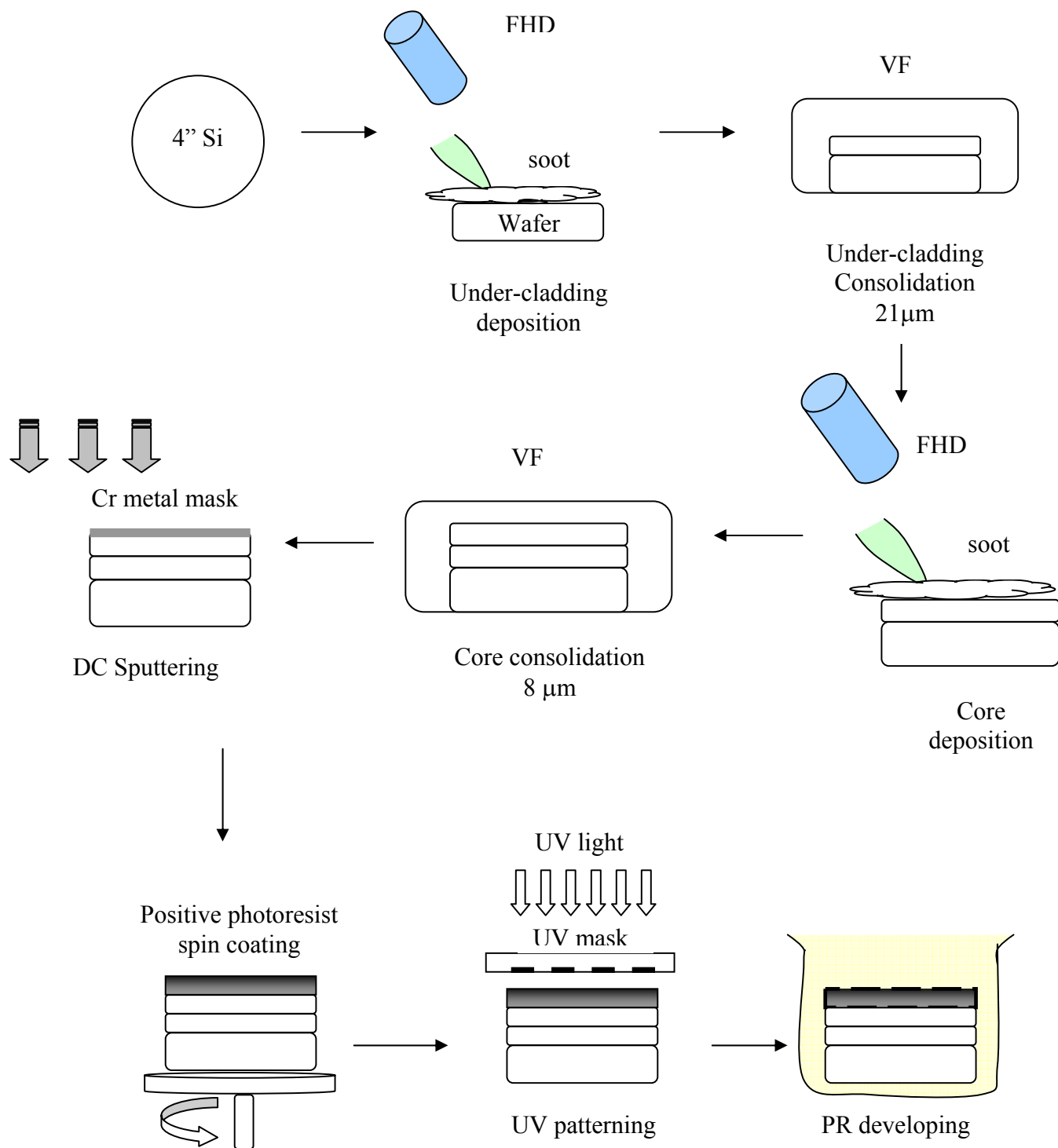
A clean room is required for PLC fabrication with minimum class of 10k and 100k for clean process and changing room, respectively. The clean room is important as dust particles on the sample during fabrication can give problems to photolithography stages and masking of the waveguide. As devices become smaller, contamination must be controlled more tightly. Protecting wafers from particles will become increasingly important. Therefore, a clean room's conditions and practices are critical. A clean room is required to maintain the cleanliness all the time and the environment quality is tested frequently by using a particle counter to ensure that the clean room is running properly. Clean room apparels are required to wear such as lint free clean suits, overshoes, gloves, hair cover and mask. Moreover, an air shower is important upon entering the clean room to remove particles and ensure minimal contamination of the environment. Room temperature and relative humidity are controlled and set at ranges between 20 to 23 °C and 45 to 55 %, respectively. Ventilation and fire-proof door are necessary for safety purpose and Desiccators are needed to store the wafer and processing samples at appropriate temperature and humidity. The clean room is maintained at appropriate

conditions to avoid the research results or products being affected by unwanted contamination.

A Yellow room is included with wet bench for photolithography, wet etching and cleaning process. For dilution, chemical mixing and cleaning need, de-ionized (DI) water is utilised. Refrigerators are also required for photoresist, and some chemicals storing is needed to maintain at low temperature.

On the other hand, desiccators are used to store partial finishing samples at certain conditions for further process. Desiccators with temperature and humidity controllers work as additional environment assurances for samples storing at independence conditions.

2.4 Process Flow



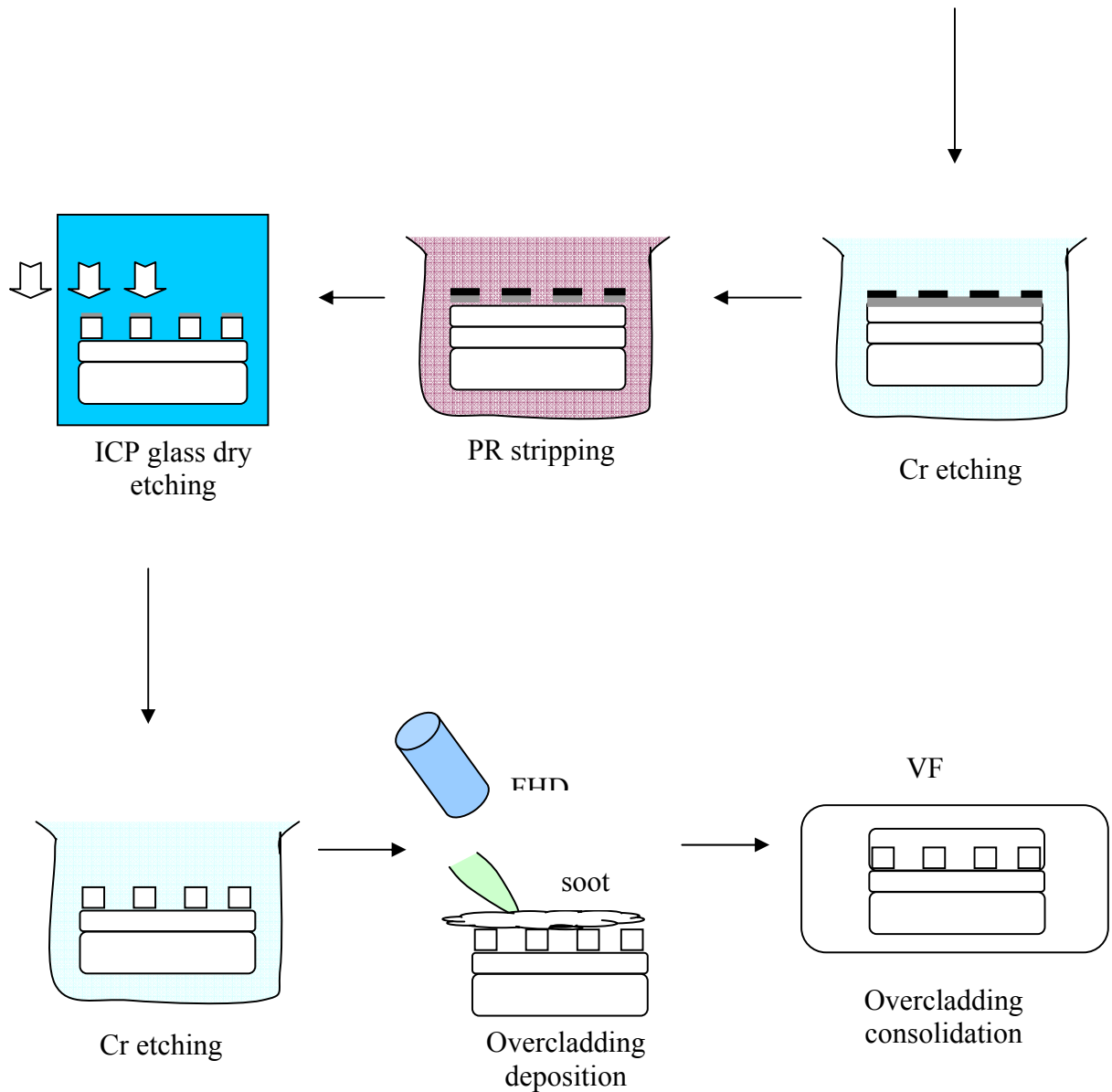


Figure 2.6: Schematic diagram of PLC fabrication process flow

Overview of PLC fabrication process flow is illustrated in figure 2.6 where in the beginning of PLC fabrication process, a clean 4 inches silicon wafer or substrate is prepared by going through the standard cleaning process and ultrasonic bath. Then, deposition of under-cladding (silica soot) layer on the silicon wafer/substrate is carried out by implementing FHD process chamber. The porous soot layer undergoes under-

cladding consolidation in vacuum furnace at certain degree Celsius to transform the soot layer to an under-cladding silica layer with thickness of about 20 micron as seen in figure 2.7. The porous soot layer is consolidated into a transparent and dense film by subsequent heat-treatment in the vacuum furnace at about 1100 °C. The consolidated under-cladding is checked under microscope for surface status and measured by prism coupler for thickness and refractive index.

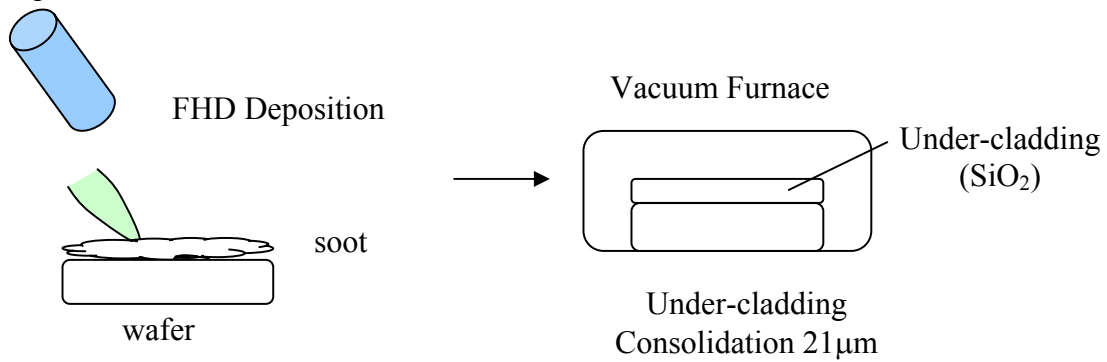


Figure 2.7: Schematic diagram of build PLC's under-cladding layer

After under-cladding consolidation, the deposition process is repeated to build the core layer upon the under-cladding layer at different ratio of composition and consolidation temperature as demonstrated in figure 2.8. The core layer has higher refractive index than the under-cladding to confine the light along its length based on total internal reflection phenomenon.

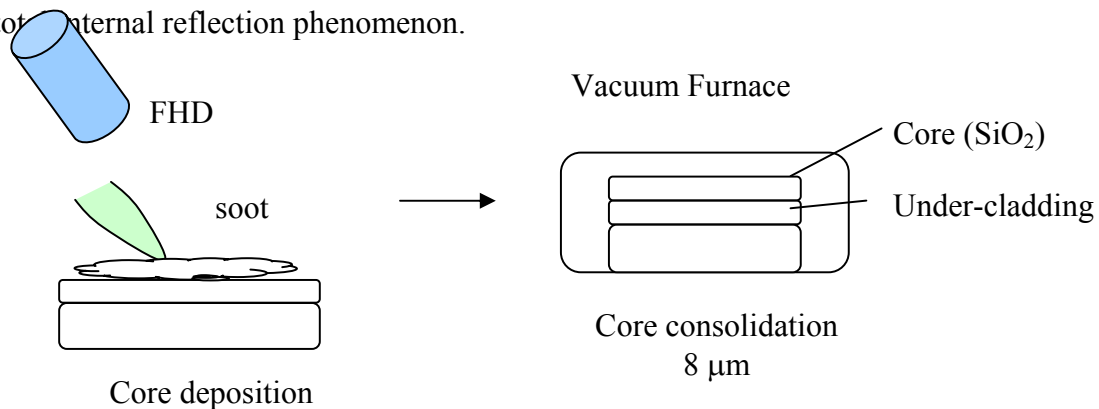


Figure 2.8: Schematic diagram of build PLC's core layer

The thickness and refractive index are measured by prism coupler after core layer been consolidated. Next, chromium metal mask is sputtered on top of core layer by DC Sputter System as shown in figure 2.9. The chromium metal mask act as hard and durable mask that prepared for critical pattern transfer process in ICP RIE glass etching.

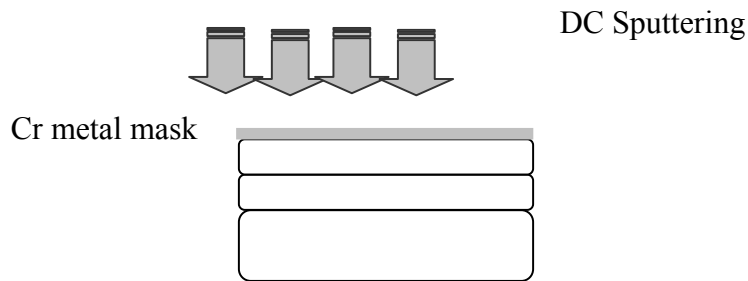


Figure 2.9: Schematic diagram of chromium metal mask sputtering

After applied photoresist (Positive PR), it's spin coating incur to achieve uniform coverage of PR as illustratec in figure 2.10. Then the wafer proceed to baking process by oven. After baked in oven for moisture removal, the PR layer is ready for the exposure process.

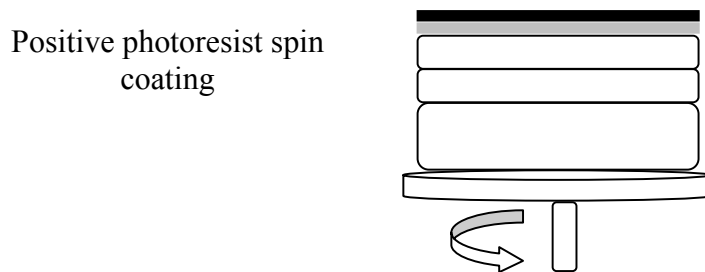


Figure 2.10: Schematic diagram of PR spin coating

Photomask is placed on the top of PR layer and expose to UV light for UV patterning. The pattern of the photomask is transferred to PR layer by softened the non-cover positive PR layer during UV exposure process as seen in figure 2.11.

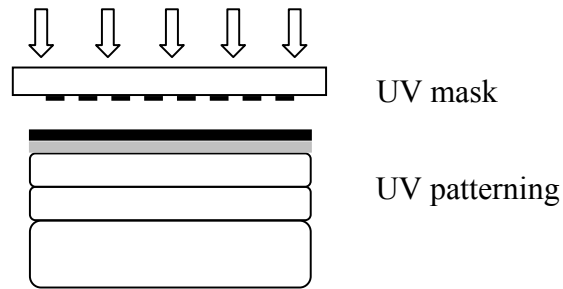


Figure 2.11: Schematic diagram of UV exposure process for pattern transfer

After UV exposure process, PR developer is used to remove unwanted PR pattern by dissolving the softened (exposed to UV) PR layer. Then, the PR pattern could be observed under microscope as illustrated in figure 2.12.

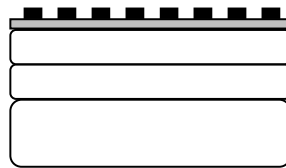


Figure 2.12: Schematic diagram of PR develop pattern

Next, the opened chromium area under PR pattern as demonstrated in figure 2.13 is then etched by using chromium etchant. The process which is called chromium etching.

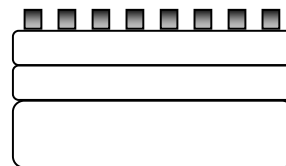


Figure 2.13: Schematic diagram of chromium etching pattern

Consequently, unwanted PR layer is removed by using PR removal or acetone. The chromium pattern is then inspected under microscope to make sure no PR residue as shown in figure 2.14 before proceed to ICP glass etching process.

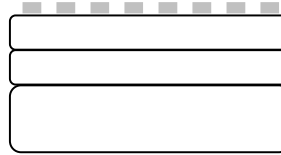


Figure 2.14: Schematic diagram of PR removing pattern

If PR residue is found after stripping process, ICP ashing is required to fully remove PR residue. For instance, Inductively Coupled Plasma (ICP) dry etching will be carry on to etch off core layer which is not covered by chromium pattern. After dry etching, the etched sample will be measured and inspected by using surface profiler and microscope as illustrated in figure 2.15 respectively; to determine either further etching process is needed or proceeds to chromium pattern removing.

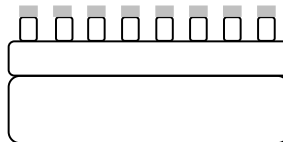


Figure 2.15: Schematic diagram of ICP etching pattern

After inspection and measurement, chromium stripping is required to remove unwanted chromium metal mask on top of core channels as seen in figure 2.16.

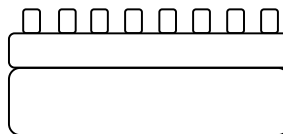


Figure 2.16: Schematic diagram of chromium stripping pattern

After chromium removing, sample is inspected under microscope to make sure chromium mask is removed fully. Finally, the sample with core channels is deposited with over-cladding by FHD and consolidated in vacuum furnace as demonstrated in figure 2.17. The thick layer of over-cladding is deposited upon core channels as buffer layer to protect core channels and prevent light pass through with lower refractive index than core channels.

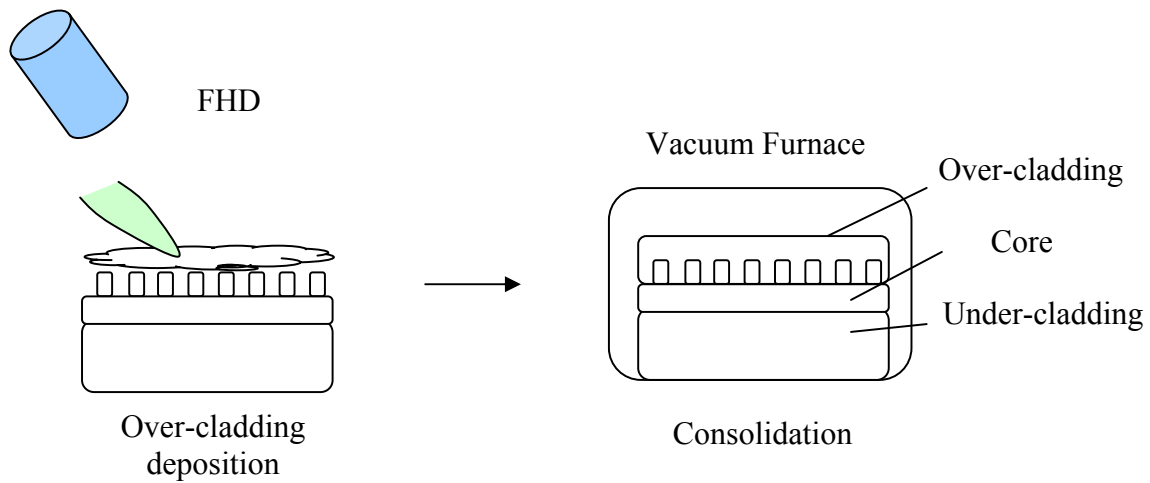


Figure 2.17: Schematic diagram of over-cladding process

2.5 Specifications and Parameters of Fabrication Process

Planar Lightwave Circuit (PLC) fabrication is mainly a process to produce silica on silicon optical chip which is compatible for applications in photonics technology. This is done by depositing and patterning silica waveguide circuit on silicon substrate that consists of FHD system, vacuum furnace, DC Magnetron Sputter system, mask aligner and ICP etcher. The fabrication process is conducted by incorporating Flame

Hydrolysis Deposition (FHD) System for silica glass deposition, vacuum furnace for glass soot consolidation and Direct Current (DC) Magnetron Sputter System for chromium deposition as metal masking. In addition, UV Mask Aligner is employed for Optical Planar Waveguide device pattern transfer and Inductively Coupled Plasma (ICP) Dry Etching System for silica etching. Included in the laboratory are also a wet-bench for wafer handling and wet chemical etching process. These are complete processes for Planar Lightwave Circuit (PLC) device fabrication.

Flame hydrolysis deposition (FHD) is a chemical process that is developed for optical fibre manufacture and it is modified to suit planar waveguide fabrication. Halides are hydrolyzed in an oxy-hydrogen flame to produce oxides in soot form, which are deposited on silicon substrates. The soot is then sintered and consolidated to produce a silica layer in the vacuum furnace.

By implementing this process it is possible to accurately control both the thickness and the refractive index of the layer that is typically matched to the optical fibre cores. These cores can be made single or multi mode by design. Once the layer has been grown it can be written by using standard photolithographic processes and dry etched. Then, cladding layers can be deposited to suit many applications. Finally, the wafer can be cut to individual chips and polished for butt-end coupling or lens alignment depending on requirements.

The optical planar waveguide fabrication process begins with 4 silicon wafers which has <100> orientation as indicated in figure 2.18. The wafer has a specification of positive type that is known as “p” type dopant and a single surface that is polished with thickness of oxidation layer at about 1.5 microns.

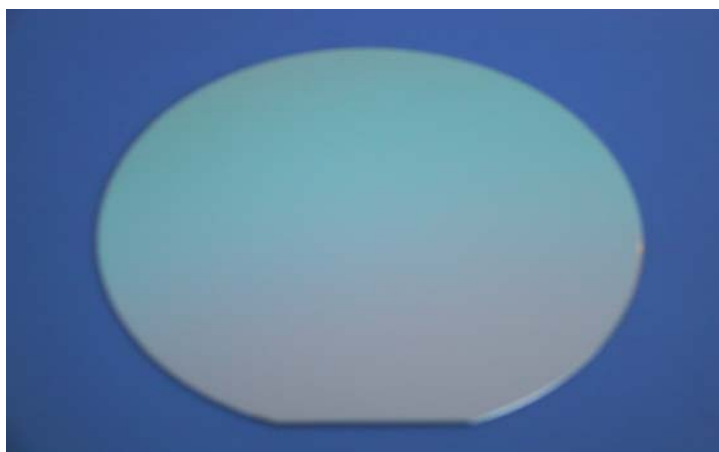
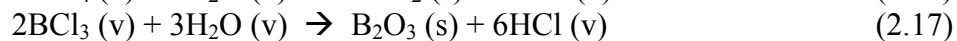
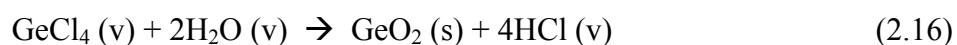
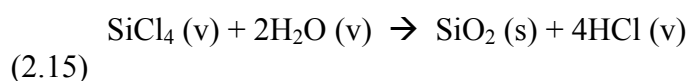


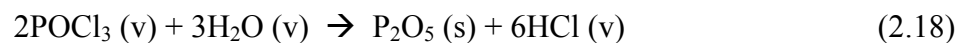
Figure 2.18: 4 inches Silicon Wafer

2.5.1 Chemical Reaction of Silica Deposition

Fine glass particles are generated in an oxy-hydrogen flame and deposited onto a wafer/substrate in the Flame Hydrolysis Deposition (FHD) System's Process Chamber. The glass particles are largely SiO_2 with a small percentage of P_2O_5 and B_2O_3 . GeO_2 is also incorporated to form glass with slightly higher refractive index.

SiCl_4 , GeCl_4 and POCl_3 in liquid forms are vaporized in a Helium carrier gas by using bubbling method. These chlorides along with BCl_3 (gas) and the carrier Helium are fed through the centre of the burner. Oxygen and Hydrogen are injected through the burner to form the flame. Hydrolysis of the chlorides occurs in the oxy-hydrogen flame to produce oxides in soot form. This process is described by the following reactions:





The porous soot layer/film is consolidated into a transparent and dense film by subsequent heat-treatment. The transfer to the Vacuum Furnace must be done carefully but as quickly as possible to avoid water related impurities.

Under-cladding and over-cladding are the same composition and it is doped with Boron (B) and Phosphorus (P) which are called as Borophosphosilicate glass (BPSG). This is a type of silicate glass that includes impurities of both boron and phosphorus. Core layer has GeO_2 doped BPSG to increase the refractive index of the silica core layer where the GeO_2 has a high refractive index for the visible light and it is also transparent to the infrared light.

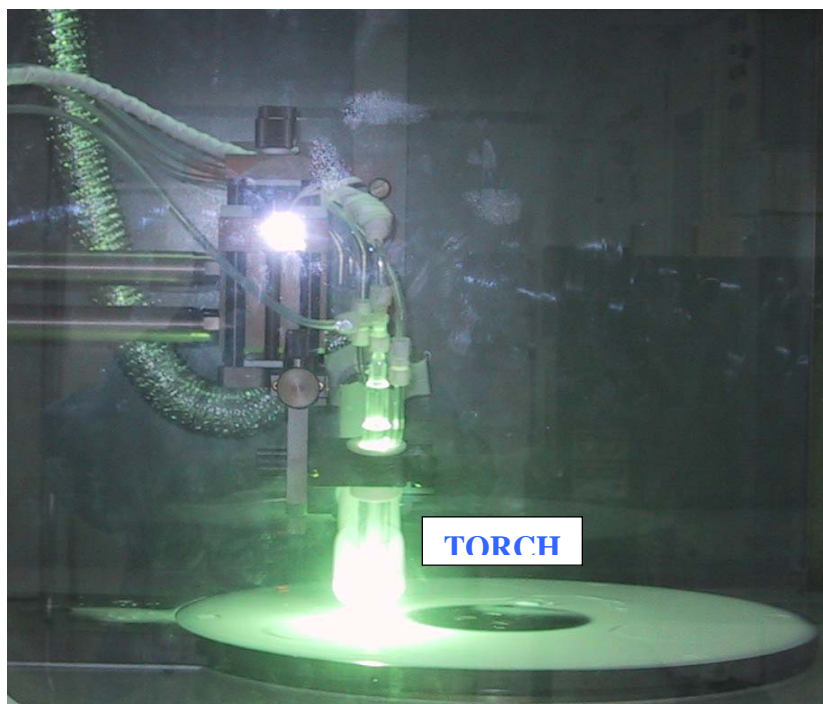


Figure 2.19: Deposition of Silica Soot in FHD System's Process Chamber

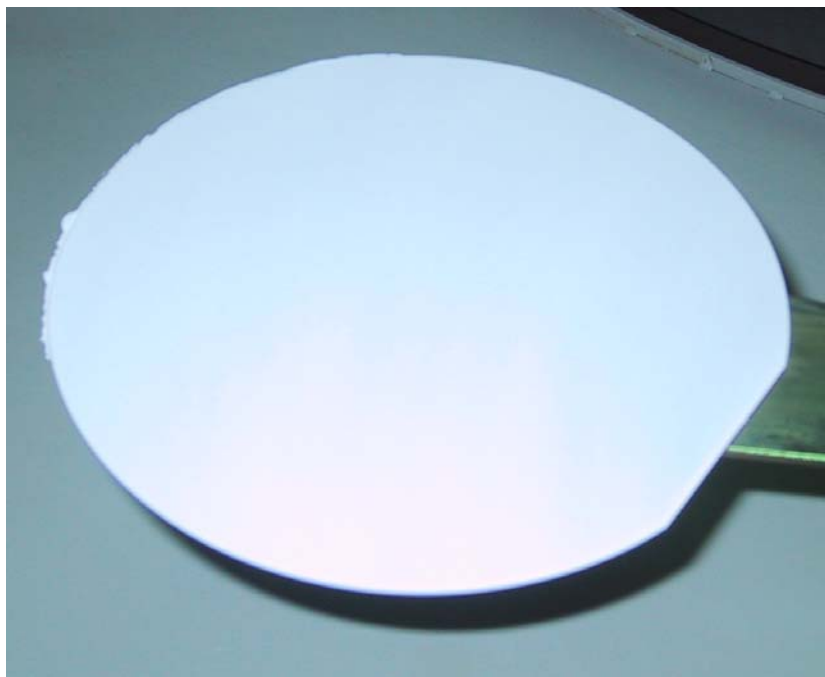
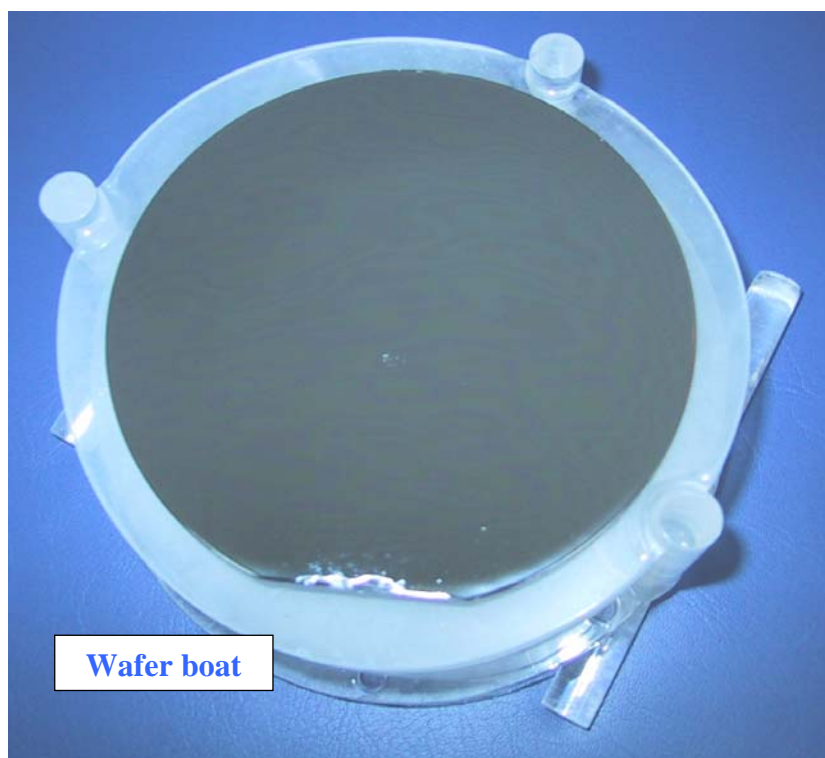


Figure 2.20: Deposited Silica in Soot Form



Wafer boat

Figure 2.21: Consolidated silica layer

The percentage of the index of refraction ($\Delta\%$) for beam splitter and AWG are about 0.3% and 0.75% respectively. On the other hand, the target of consolidated glass layer's thickness and refractive index measurements by Prism Coupler are presented in table 2.3.

Table 2.3: Target of thickness and refractive index for under-cladding, core and over-cladding layers

Layer	Thickness	Refractive Index
Under-cladding	15 – 20 μm	1.4420-1.4440
Core	8 μm	1.4460-1.4500
Over-cladding	15 – 20 μm	1.4420-1.4440

2.5.2 Specifications of Chromium Layer

The Chromium layer is deposited onto the wafer by incorporating a DC Sputter System. In this system, stable burning plasma is generated in a low pressure chamber that is filled with Argon by applying a negative potential to the target. This produces accelerating Argon ions which hit the target and the material to detach (sputter) onto the substrate.

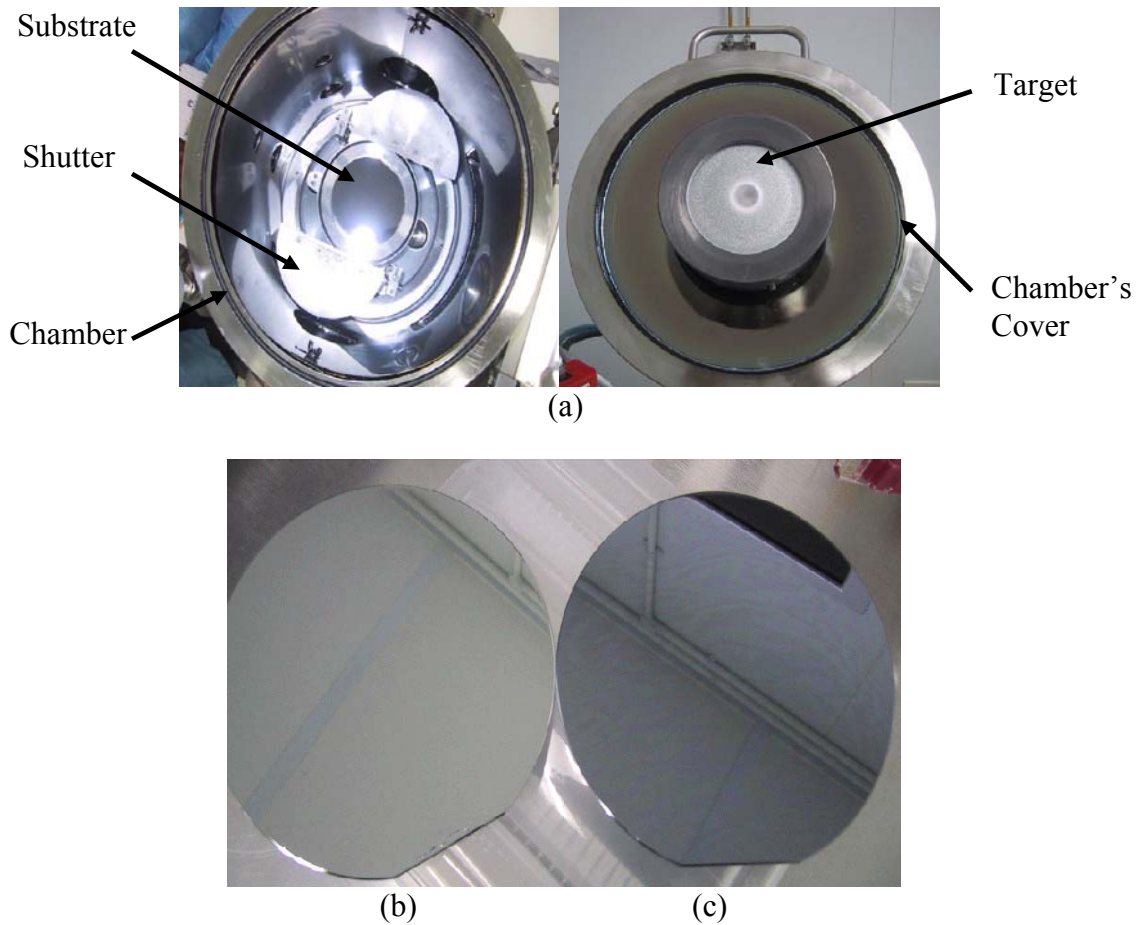


Figure 2.22: (a) Sputter Chamber, (b) substrate after and (c) substrate before the Chromium deposition. The coated Chromium layer has a mirror finish surface.

2.5.3 Parameters of Photolithography

Few processes are involved in the pattern transfer from a quartz photomask to the Photoresist (PR) layer. The first are applications of PR Layer by implementing spin coater. The wafer is placed on a wafer chuck and PR solution is dispensed by pipette onto the Chromium coated sample where the sample is spun to obtain an evenly distributed PR layer. A visual inspection is done to check the PR application. The PR solution from a refrigerator require about 15 minutes to reach clean-room temperature before it can be

used. When this is achieved, about 3-5 ml PR solution is then prepared without bubbles while dispensing by using pipette. At the mean time, the spin coating begins with appropriate spin process condition for the thickness of PR layer at about 1 micron. The PR spin coating photo is depicted in figure 2.23.

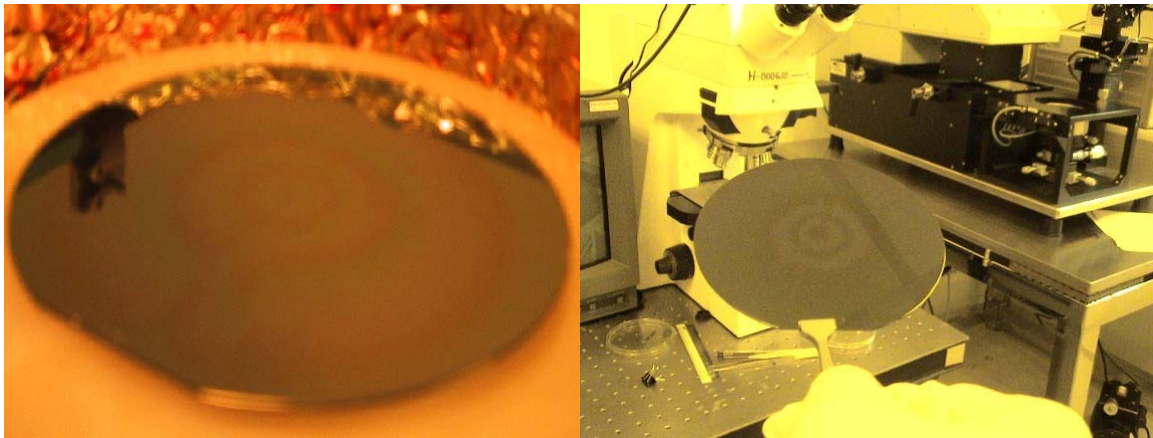


Figure 2.23: Symmetrical ring pattern observed on the wafer surface that indicates an even distribution of the spin coated PR layer

Next, Soft-bake step with a hot plate at 100°C is done for about 2 minutes to harden the PR layer. The layer is then cooled down for 3-5 minutes at room temperature before proceeding to mask aligning and UV exposure that incorporate Mask Aligner System. After 20 minutes of UV lamp warm up and mask aligning process, the sample is exposed to UV lamp that is set at 205W output power and 2mW/cm² intensity for 10 seconds.

After UV exposure, the wafer is immersed into a PR developer for around 1 minute (observe the surface changes until they stops). It is blown dry after the PR development and proceed to Hard-bake process at 115°C for 10 minutes in the oven. The

wafer is then cooled down and inspected with microscope. The next step is performing chromium etching after microscope inspection.

On the other hand, chromium wet etching must be less than 25 minutes and it is rinsed with DI water for about 1 minute. After chromium etching process, UV exposed PR pattern is removed or stripped with acidic PR Remover or acetone for 5 minutes. PR Remover is preferred in order to achieve better stripping result.

2.5.4 Silica Core Etching Using ICP Etching System

The objective of this process is to transfer the chromium mask pattern onto silica core layer by using ICP Etching System. This is a critical development that engineers and patterns the silica core layer to guide the light source through the channels at low loss.

After ICP etching process, the sample will be inspected with some measurement and analysis equipments such as surface profiler, frame capture microscope system, SEM, AFM and etc. Once these are performed, the chromium is removed in the following process where details and results will be presented in the following chapter.

2.5.5 Over-cladding Deposition

Finally, the over-cladding is deposited onto ICP etch wafer. The content of over-cladding is the same as the under-cladding layer which consists of largely SiO_2 with P_2O_5 and B_2O_3 . However, higher percentage of P_2O_5 and B_2O_3 is contained in the over cladding layer to lower the consolidation temperature which avoid the deformation of

ICP etched core profile. Otherwise, over-cladding plays importance roles as a buffer layer and to protect the core channel. After consolidation by vacuum furnace at about 900°C, the finished product is demonstrated in figure 2.24.

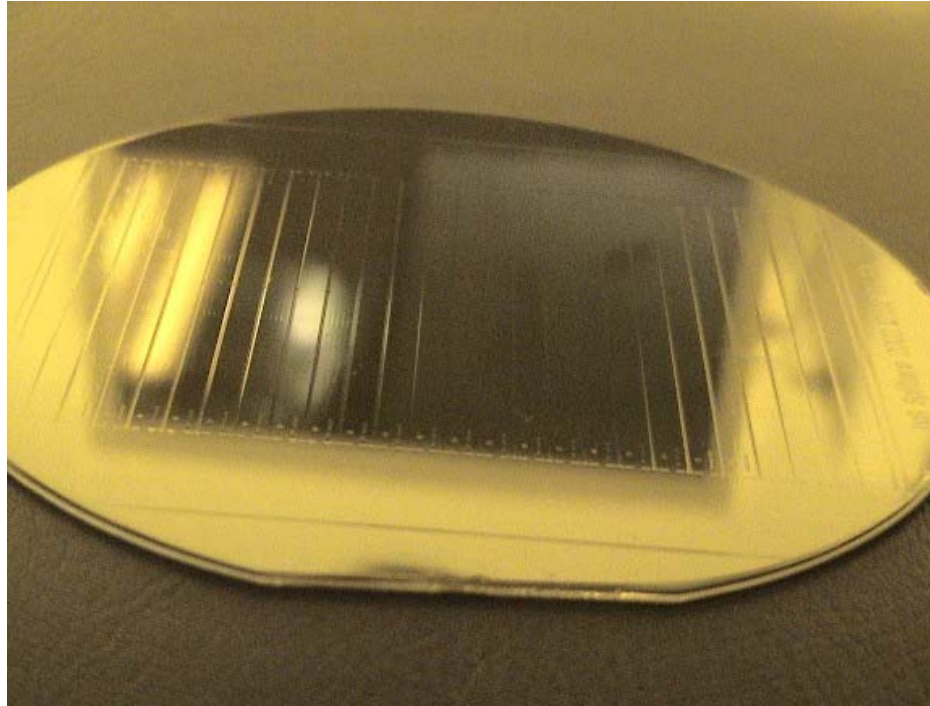


Figure 2.24: Planar Lightwave Circuit wafer with over-cladding layer

References

- [1] Kilian et al., J. Lightwave Technology, vol. 18, pp. 193, 2000.
- [2] T. Miya, IEEE J. Sel. Top. Quantum Electron, Vol. 6, pp. 38, 2000.
- [3] H. Takahashi et al., Electron Letter, Vol. 31, pp. 723, 1995.
- [4] O. Brand, "Fabrication Technology", Advanced Micro and Nanosystems. Vol. 2. CMOS – MEMS, 2005.
- [5] Jaeger, Richard C. (2002). "Lithography", Introduction to Microelectronic Fabrication. Upper Saddle River: Prentice Hall. ISBN 0-201-44494-7.
- [6] ^{a b c} D. O. S. Melville and R. J. Blaikie, Optics Express vol. 13, pp. 2127-2134 (2005)
- [7] O. J. F. Martin et al., Optics Express vol. 3, pp. 280-285 (1998)
- [8] X. Cheng and L. J. Guo, Microelectronic Eng. 71, pp. 277-282 (2004)
- [9] Hand, Aaron. High-Index Lenses Push Immersion Beyond 32 nm.

- [10] 1997 SPIE interview with Burn Lin
- [11] S. J. McNab and R. J. Blaikie, *Appl. Opt.* vol. 39, pp. 20-25 (2000)
- [12] ^{a b c} X. Luo and T. Ishihara, *Optics Express* vol. 12, pp. 3055-3065 (2004)
- [13] J. A. Porto et al., *Phys. Rev. Lett.* vol. 83, pp. 2845-2848 (1999)
- [14] ^{a b} X. Jiao et al., *Progress in Electromagnetics Research Symposium 2005*, pp. 1-5 (2005)
- [15] D. R. Smith et al., *Appl. Phys. Lett.* vol. 82, pp. 1506-1508 (2003)
- [16] L. Salomon et al., *Phys. Rev. Lett.* vol. 86, pp. 1110-1113 (2001)
- [17] W. Srituravanich et al., *Nano Lett.* vol. 4, pp. 1085-1088 (2004)
- [18] C. P. Ausschnitt, A. C. Thomas, and T. J. Wiltshire, *IBM J. Res. Develop.* 41, No. 1, 21 (1997)
- [19] P Heimala *et al.*, "Refractive index behaviour of phosphorus-doped planar silica waveguides," 1992 *J. Phys. D: Appl. Phys.* **25** 733-739
- [20] N. Takato, M. Yasu, M. Kawachi, *Electron. Lett.* 22 (6) (1986) 321.
- [21] M. Kawachi, M. Yasu, T. Eda Hiro, *Electron. Lett.* 19 (15) (1983) 583.
- [22] T. Kominato, Y. Ohmori, et al., *Electron. Lett.* 26 (5) (1990) 327.
- [23] M. Kawachi, M. Yasu, M. Kobayashi, *Jpn. J. Appl. Phys.* 22 (12) (1983) 1932.
- [24] Y. Wu, H. Xing, L. Zhang, et al., *Apoc 2001*, Beijing, SPIE 4580 251.
- [25] L. Zhang, W. Xie, Y. Wu, H. Xing, A. Li, W. Zheng, Y. Zhang, "Optical and surface properties of SiO₂ by flame hydrolysis deposition for silica waveguide," *Optical Materials* 22, pp. 283-287, 2003.
- [26] Y. T. Kim et al, "Influence of Hydrogen on SiO₂ Thick Film Deposited by PECVD and FHD for Silica Optical Waveguide," *Cryst. Res. Technol.*, Vol. 37, no. 12, pp. 1257 – 1263, (2002).
- [27] Hyungsoo Shin et al, "Preparation and Characterization of SiO₂-B₂O₃-P₂O₅ Particles and Films Generated by Flame Hydrolysis Deposition for Planar Light-Wave Circuits," *J. Mater. Res.*, Vol. 27, no. 2, pp. 315 – 322, (2002).
- [28] Jaeger, Richard C. (2002). "Thermal Oxidation of Silicon", *Introduction to Microelectronic Fabrication*. Upper Saddle River: Prentice Hall. ISBN 0-201-44494-7.
- [29] S.M. Rossnagel, "Sputter deposition for semiconductor manufacturing", *IBM J. Res. Develop.* vol. 43, no. 1-2 (31 ref.), pp. 163-179, 1999
- [30] Steiner, "Semiconductor Nanostructures for Optoelectronic Applications", Norwood, MA, USA: Artech House, Incorporated, p33, 2004.
- [31] Hartmut Frey, editor. Band 1, *Plasmaphysik – Plasmadiagnostik – Analytik. Vakuumbeschichtung*. VDI-Verlag, Düsseldorf, 1995. ISBN 3-18-401313-6.
- [32] Thomas Luyven. *Dünnschichtsysteme für Low-E-Anwendungen: Der Einfluß des Sputterns auf Silberfilme in Mehrschichtsystemen*. Dissertation, RWTH Aachen, 1999.
- [33] Oliver Kappertz. In Vorbereitung. Dissertation, RWTH Aachen.
- [34] Oliver Kappertz, Robert Drese, and Matthias Wuttig. Correlation between structure, stress and deposition parameters in DC-sputtered zinc oxide films. submitted to: *Journal of Vacuum Science and Technology A*.

- [35] Christian Salinga, Hansjörg Weis, and Matthias Wuttig. Gasochromic switching of tungsten oxide films: A correlation between film properties and coloration kinetics. submitted to: Thin Solid Films, 2002.
- [36] R. Wendt and K. Ellmer. Desorption of Zn from a growing ZnO:Al-film deposited by magnetron sputtering. Surface and Coatings Technology, 93(1):27–31, 1997.
- [37] R. Wendt, K. Ellmer, and K. Wieseemann. Thermal power at a substrate during ZnO:Al thin film deposition in a planar magnetron sputtering system. J. Appl. Phys., 82(5):2115–2122, 1997.

CHAPTER 3

ETCHING

In etching, the objective is to selectively remove material by using imaged photoresist (PR) or metal as a masking template. The pattern can be etched directly into the substrate or into a thin film, which may in turn be used as a mask for subsequent etches. For a successful etch, there must be sufficient selectivity (etch-rate ratio) between the material being etched and the masking material. Etch processes in PLC fabrication deviates from traditional mechanisms from integrated circuit industry as it had large extent in state-of-the-art techniques.

Etching is a critically important process module, and every wafer undergoes many etching steps before it is complete. For many etch steps, part of the wafer is protected from the etchant by a masking material which resists etching. In some cases, the masking material is photoresist which has been written by implementing photolithography. Other situations require a more durable mask, namely metal mask or silicon nitride.

If the etch is intended to make a cavity in a material, the depth of the cavity may be controlled approximately by using the etching time and the known etch rate. More often, etching must entirely remove the top layer of a multilayer structure without damaging the underlying or masking layers. The etching system's ability to do this

depends on the ratio of etch rates in the two materials that is known as selectivity. Some etches undercut the masking layer and form cavities with sloping sidewalls. The distance of undercutting is called bias. Etchants with large bias are called isotropic because they erode the substrate equally in all directions. Modern processes greatly prefer anisotropic etches because they produce sharp, well-controlled features.

The two different categories of etching processes include wet etching that utilises liquid chemicals and dry etching that utilises gas-phase chemistry. Both methods can be either isotropic or anisotropic. The important criteria for selecting a particular etching process encompass the material etch rate, the selectivity for the material to be etched, and the isotropy/anisotropy of the etching process.

Wet etching is usually isotropic with the important exception of anisotropic silicon wet etching especially in alkaline solutions that include potassium hydroxide. Moreover, wet etching typically provides a better etch selectivity for the material to be etched in comparison to other neighbouring materials. An example includes wet etching of silicon dioxide that uses hydrofluoric acid-based chemistries. Silica (SiO_2) is isotropically etched in dilute hydrofluoric acid ($\text{HF-H}_2\text{O}$) or buffered oxide etch, BOE ($\text{HF-NH}_4\text{F}$). Typical etch rates for high-quality (thermally grown) silicon dioxide films are 0.1 $\mu\text{m}/\text{min}$ in BOE.

Dry etching on the other hand is often anisotropic that results in a better pattern transfer as mask under-etching is avoided. Therefore, anisotropic dry etching processes particularly reactive ion etching (RIE) of thin-film materials are very common in the microelectronics industry. In an RIE system, reactive ions are generated in plasma and are accelerated towards the surface to be etched, thus providing directional etching

characteristics. Higher ion energies typically result in more anisotropic etching characteristics, but also in reduced etching selectivity.

Dry etching is a complex technology that is expensive to run compared to wet etching, but it results in good feature resolution in thin film structures and vertical sidewalls for deep etchings in the substrate. Theoretically, etching thin films is relatively easier than that of bulk silicon or silicon dioxide. Table 3.1 provides a list of wet and dry (usually plasma) etchants that are commonly used for metal and dielectric films. Deep etching of silicon dioxide lies at the core of what is often termed as bulk micromachining. No ideal silicon dioxide etch method exists, leaving process engineers with techniques that are suitable for some applications but not others. Distinctions are made on the basis of isotropy; etch medium and selectivity to other materials.

Table 3.1: Typical wet and dry etchants of thin metal films and dielectric insulators [1, 2]

Material Type	Wet Etchants	Dry Etching Gases
Thermal silicon oxide	HF Buffered Oxide Etchant	CHF ₃ +O ₂ CHF ₃ +CF ₄ +He HF vapour
LPCVD silicon nitride	Hot H ₃ PO ₄	SF ₆ CHF ₃ +CF ₄ +He
Aluminum	Warm H ₃ PO ₄ :HNO ₃ :CH ₃ COOH HF	Cl ₂ +SiCl ₄ Cl ₂ +BCl ₃ +CHCl ₃
Gold	KI:I ₂	
Titanium	HF:H ₂ O ₂	SF ₆
Tungsten	Warm H ₂ O ₂ K ₃ Fe(CN) ₆ :KOH:KH ₂ PO ₄	SF ₆
Chromium	Ce(NH ₄) ₂ (NO ₃) ₆ :CH ₃ COOH	Cl ₂
Photoresist	Hot H ₂ SO ₄ :H ₂ O ₂ CH ₃ COOH ₃ (Acetone)	O ₂

Isotropic etchants etch uniformly in all directions, resulting in rounded cross sectional features. By contrast, anisotropic etchants etch in some directions preferentially over others. This leads to trenches or cavities delineated by flat and well defined surfaces,

which need not to be perpendicular to the surface of the wafer as illustrated in figure 3.1. Etch medium plays a role in selecting a suitable etch method that is either wet or dry etching. Wet etchants in aqueous solutions offer the advantage of low-cost batch fabrication where 25 to 50 wafers with 100-mm-diameter can be etched simultaneously and they can be either of the isotropic or anisotropic type. Dry etching involves the use of reactant gases, usually in low-pressure plasma but non plasma gas-phase etching is also used to a small degree. The equipment for dry etching is specialized and requires the plumbing of ultra-clean pipes to bring high purity reactant gases into the vacuum chamber.

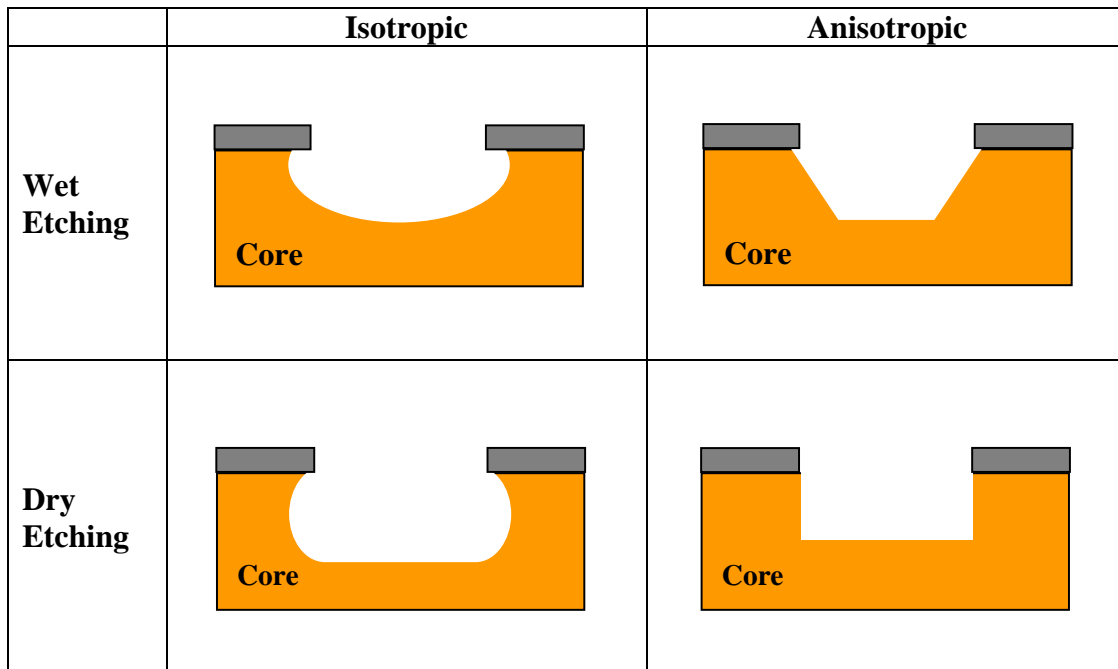


Figure 3.1: Schematic illustrations of cross-sectional trench profiles resulting from four different types of etch methods.

3.1 History and Background

Etching by goldsmiths and other metal-workers is performed in order to decorate metal items such as guns, armour, cups and plates. It has been known in Europe at least since the Middle Ages and may go back to antiquity. The elaborate decoration of armour in Germany was an art that was probably imported from Italy around the end of 15th century, which is a little earlier than the birth of etching as a printmaking technique. The process that is applied to printmaking is believed to have been invented by Daniel Hopfer (circa 1470-1536) of Augsburg, Germany. The switch to copper plates was probably made in Italy, and thereafter etching soon came to challenge engraving as the most popular medium for artists in printmaking. Unlike engraving that requires special skill in metalworking, etching is relatively easy to learn for an artist that is trained in drawing.

Jacques Callot (1592-1635) from Nancy in Lorraine (now part of France) made important technical advances in etching technique. He developed the *échope*, a type of etching-needle with a slanting oval section at the end which enabled etchers to create a swelling line, as engravers were able to do. Now etchers could do the highly detailed work that was previously monopolised by engravers as Callot had utilised the new possibilities.

The 17th century was the great age of etching with the involvement of Rembrandt, Giovanni Benedetto Castiglione and many other masters. In the 18th century Piranesi, Tiepolo and Daniel Chodowiecki were the best artist from a smaller number of fine etchers. In the 19th and early-20th century the etching revival produced a host of

lesser artists, but no really major figures. However, etching is still widely practiced today.

3.2 Wet Etching

In this technique, an aqueous chemical solution is involved where the chemical reaction is isotropic, thus resulting in rounded cross-sectional features. The most common group of silicon or silicon oxide isotropic wet etchants is HNA that is also known as iso-etch and poly-etch because of its use in the early days of the integrated circuit industry as an etchant for polysilicon. It is a mixture of hydrofluoric (HF), nitric (HNO_3), and alternatively acetic acids (CH_3COOH) as water may replace the acetic acid. In the chemical reaction, the nitric acid oxidizes silicon which is then etched by the hydrofluoric acid. The acetic acid controls the dissociation of HNO_3 which provides the oxidation of the silicon. The etch rate of silicon can vary from 0.1 to over 100 $\mu\text{m}/\text{min}$ depending on the proportion of the acids in the mixture. Etch uniformity is normally difficult to control but it is improved by stirring.

Several wet etchings are anisotropic where this process that incorporates silicon substrate is the most common micromachining technique that is used to release, for instance membrane and beam structures. Anisotropic wet etchants are also known as orientation-dependent etchants (ODEs) because their etch rates depend on the crystallographic direction. For example, the list of anisotropic wet etchants includes the hydroxides of alkali metals. These are Sodium Hydroxide (NaOH), Potassium

Hydroxide (KOH), Cesium Hydroxide (CsOH); simple and quaternary Ammonium Hydroxides (e.g., NH_4OH , $\text{N}(\text{CH}_3)_4\text{OH}$), and Ethylene Diamine mixed with Pyrochatechol (EDP) in water [3]. The solutions are typically heated to $70\text{ }^\circ\text{C} - 100\text{ }^\circ\text{C}$ and a comparison of various silicon etchants is given in Appendix 1.

The advantages of wet etching is costly efficient, high etch rate and useful for certain process especially in bulky compound material. In contrast, there are some limitations that restrict dry etching performance for well controlled and high precision, where critical dimension in small feature size process is required.

3.3 Dry Etching

Dry etching is also called as plasma etching or plasma-assisted etching. It provides two modes of etching that are either isotropic or anisotropic. In isotropic etching, no potential is applied between the sample and glow discharge. Anisotropic etching is a major advantage of plasma etching where the wafer surface is subjected to energetic ion bombardment as this offers dimensional control to delineate small features with acceptable yield.

Basically, atoms created by electron impact dissociation of etch gas react with the surface to form volatile compounds which are carried into the gas phase and swept away from the process chamber. In dry etching process, atoms created by electron impact dissociation of etch gas react with the surface to form volatile compounds which are carried into gas phase and swept away. Plasma in dry etching system performs two basic

functions where the first is to generate chemical species by electron-impact collisions, and the second is to bombard the surface with energetic species such as electrons, positive ion, neutrals, metastables and photons.

Plasma etching involves the generation of chemically reactive neutrals (eg, F, Cl), and ions (eg, CF_x^+) that are accelerated under the effect of an electric field toward a target substrate. The reactive species (neutrals and ions) are formed by the collision of molecules in a reactant gas (eg, SF_6 , O_2 , CF_4 , C_2F_6 , CHF_3 , NF_3) with a cloud of energetic electrons that is excited by an RF electric field. When the etch process is purely chemical and it is powered by the spontaneous reaction of neutrals with surface material, it is colloquially referred to as plasma chemical etching. When ion is accelerated and strikes a substrate with high kinetic energy, physical sputtering or ion milling happens that leads to material removal. But if ion bombardment of the surface material plays a synergistic role in the chemical etch reaction; the process is then referred to as Reactive Ion Etching (RIE). In RIE, ion motion toward the substrate is nearly vertical which gives this technique vertical anisotropy etches. Asymmetric electrodes and low chamber pressures are characteristics of RIE operation. RIE provides greater excitation to the electron cloud by means of an externally applied RF electromagnetic field which increases the density of ions and neutrals that result in higher etch rates. The ion bombardment energy is controlled by a separate power supply that drives the platen on which the wafer sits.

A different, purely physical method of etching is ion milling where noble-gas ions, usually argon ion are remotely generated, then accelerated at the substrate through a potential on the order of kilovolts. The directionality of the ions results in a good vertical etches profile. As a chemical reaction is not required, any material can be etched by ion

milling. The ion-milling rate is typically much slower than with RIE and it varies widely with the material [1].

In addition to RIE dry etch system, Deep Reactive Ion Etching (DRIE) evolved in the mid 1990s due to the need in the micromachining industry to search for a new etch process. It is capable to achieve high-aspect-ratio trenches vertically at rates that are substantially larger than 0.1 to 0.5 $\mu\text{m}/\text{min}$ which is typical for traditional plasma and RIE etchers. In an approach that is developed by Alcatel, the wafer is cooled to cryogenic temperatures. Condensation of the reactant gases that consist of a passive layer, protect the sidewalls from etching by the reactive fluorine atoms. However, cryogenic cooling may be difficult to maintain locally and could result in undesirable thermal stresses.

The introduction of deep reactive ion etching (DRIE) system by several companies such as Surface Technology Systems Ltd. (STS), Newport, Unaxis Semiconductors (formerly PlasmaTherm) and Alcatel S. A. provides a new powerful tool for etching very deep trenches (over 500 μm) with nearly vertical sidewalls. Another approach that is currently used by Alcatel, PlasmaTherm, and Surface Technology Systems (STS) [2] follows a method patented by Robert Bosch GmbH of Stuttgart, Germany in which etch and deposition steps alternate in an ICP-RIE system [3]. The etch part of the cycle that typically lasts for 5 to 15 s uses SF_6 , which supplies highly reactive fluorine radicals to etch silicon dioxide. The etch step has both vertical and isotropic characters, resulting in a slight mask undercut. In the deposition step, a fluorocarbon polymer (made of a chain of CF_2 groups similar in composition to TeflonTM) of about 10 nm thick is plasma-deposited by utilising C_4F_8 as the source gas. In the following etch step, the vertically oriented ions (SF_x^+) enhance the effect of fluorine radicals in

removing the protective polymer at the bottom of the trench while the film remains relatively intact along the sidewalls. The repetitive alternation of etching and passivation steps result in a directional etch at rates from 1 $\mu\text{m}/\text{min}$ and up to 15 $\mu\text{m}/\text{min}$ depending on the recipe and machine (newer etchers are available with more powerful RF sources). The degree of scalloping the sidewall texture due to the isotropic component of etching varies with the recipe. Recipes that are optimized for smoother sidewalls can exhibit surface planarity with roughness less than 50 nm, allowing their use for optically reflective surfaces.

DRIE is a powerful tool for the formation of deep trenches with near-vertical sidewalls. However, process development is required for each mask pattern and depth to optimize for low ARDE, good uniformity, high speed, high verticality, small scalloping, and small footing. In general, all cannot be optimized simultaneously. Sequentially running different processes or slowly changing the process as the etch proceeds may be done for the best result. A limitation of DRIE is the dependence of etch rates on the aspect ratio (ratio of height to width) of the trench. The effect is known as lag or aspect-ratio-dependent etching (ARDE). The etch rate is limited by the flux of reactants (namely, F radicals) and drops significantly for narrow trenches. A quick remedy is implemented at the mask layout stage by eliminating large disparities in trench widths. The effect of lag can also be greatly alleviated by adjusting the process parameters such that a balance is reached between the transport-limited rates of etching and passivation steps [4]. However, when etch reaches the buried oxide layer, the positive ions charge the oxide to deflect subsequent ions to the side. The ion bombardment degrades the

passivation layer at the bases of the sidewalls, resulting in an undesirable lateral undercut (referred to as footing or notching) along the silicon-oxide interface.

3.3.1 Principle of Dry Etching

The first step of dry etching is to generate plasma with gas form of etch agent in a variety of vacuum range from low to high vacuum condition that is appropriate to process requirement. In dry etching process, atoms created by electron impact dissociation of etch gas react with the surface to form volatile compounds which are carried into gas phase and swept away.

Analogous to wet etching, dry etching also follows the resist mask patterns on the wafer. It only etches away materials that are not covered by mask material while leaving areas that are covered by the masks almost intact. These masks are deposited on the wafer by an earlier wafer fabrication step that is known as lithography.

Directional etching is the major advantage of plasma etching where the result of energetic ion bombardment and etching rate usually increased by the creation of energetic ions in plasma containing active neutral species. Ions in a glow discharge usually strike normal to surface. Thus, the bottom of a feature is subjected to energetic ion bombardment whereas the sidewalls are exposed primarily to neutral species. Basically, bottom etch rate is larger because of it is ion-assisted and sidewall etch rate is small whereas it receive few energetic ions.

In general, dry etching categories into three groups which are chemical, physical and combination of chemical and physical etching. In chemical etching, its result

isotropic and high selectivity etch by using chemically reactive gases or plasma but often induced under-cut. Physical etching which purely etches with sputtering effect that usually by momentum transfer where provides anisotropic but low selectivity, for instance ion milling etching process. On the other hand, combination of chemical and physical etching that known as Reactive Ion Etching (RIE) enable directional etch due to ion assistance and enhance chemical etching mechanisms with negative bias which result in enhance anisotropic etch and better line width control.

Further more, dry etching process can classified into four different etching methods which are gas/vapour etching, plasma etching, sputtering etching and reactive ion etching. In dry etching, primary process sequence in plasma-assisted etching begins with creation of reactive species by electron-molecule collisions in plasma. The adsorption of etching species occurs when diffusion of reactive flux to surface and reaction to form product which are called etch product and by-product. At the mean time, desorption of volatile products also occur together with diffusion of products away from surface.

The selectivity of the species used in dry etching that employs chemical reactions is very important. Selectivity refers to the ability of the reactive species to etch away only the material intended for removal, while leaving all other materials intact. In particular, the species used must not attack the mask material over the material being etched as well as the material beneath it.

In general, the reactive species used in dry chemical etching required the criteria as the following: 1) high selectivity against etching the mask material over the layer being etched; 2) high selectivity against etching the material under the layer being

etched; 3) high etch rate for the material being removed; and 4) excellent etching uniformity. More over, it's also required to provide a safe, clean, and automation-ready etching process.

Another important consideration in any etching process is its anisotropy, or property of etching in one direction only. A completely anisotropic etching process that removes material in the vertical direction only is very desirable, since it will follow the mask patterns on the wafer very faithfully, leaving any material covered by mask material basically untouched.

Unfortunately, most etching techniques that employ purely chemical means to remove the material whether through wet or dry etching do not exhibit high anisotropy. This is because chemical reactions can and do occur in all directions. Thus, chemical reactions can attack in the horizontal direction and consume a portion of the material covered by the mask, a phenomenon known as undercutting.

If maximum anisotropy is of utmost concern, then dry etching techniques that employ physical removal of material must be considered. One such technique is physical sputtering, which involves purely physical removal of material by bombarding it with highly energetic but chemically inert species or ions. These energetic ions collide with atoms of the material as they hit the material's surface, dislodging these atoms in the process.

Targeting the layer to be etched with incident ions that are perpendicular to its surface will ensure that only the material not covered by the mask will be removed. Unfortunately, such a purely physical process is also non-selective, i.e., it also attacks the mask layer covering the material being etched, since the mask is also directly hit by

the bombarding species. For this reason, physical sputtering has never become popular as a dry etching technique for wafer fabrication.

A good balance between isotropy and selectivity may be achieved by employing both physical sputtering and chemical means in the same dry etching process. Reactive Ion Etching (RIE) is one such process that involves both physical and chemical means to remove material. Sometimes, RIE is referred to as reactive sputter etching (RSE), consists of bombarding the material to be etched with highly energetic chemically reactive ions. Such bombardment with energetic ions dislodges atoms from the material as purely physical sputtering, in effect achieving material removal by sputtering.

In addition to sputter-removal, the bombarding ions used in RIE would chemically react with the material being bombarded to produce highly volatile reaction by-products that can simply be pumped out of the system. RIE is widely used in wafer fabrication as it achieves the required anisotropy which by means of sputter-removal and the required selectivity through chemical reactions.

The properties of plasma used for etching and deposition of thin films which used the RF frequencies and pressure range from 50 kHz to 40 MHz and 5 to 5000 mTorr respectively. The preference of RF plasma over DC plasma which are sustaining the plasma at lower pressure (long mean free path) and RF allow etching of dielectric as well as metals. In order to fabricate silica on silicon devices, the RF plasma chosen as to engineer the dielectric layer of silica core.

3.3.2 Fundamental of Plasma

Plasma is typically an ionized gas that exists in a distinct state of matter, apart from gases. It consists of freely moving charged particles which contains some or all of the components such as electron, positive ions, atoms and molecules. The plasma is generated and maintained via collisions to produce a certain distribution of ionic and neutral species in the vacuum chamber. This is comparable to the preliminary process to start dry etching and further description of the fundamental is stated in Appendix 2.

3.3.3 Plasma Processing

Plasma processing is a plasma-based material processing technology that aims at modifying the chemical and physical properties of a surface that can be either in semiconductor or photonics fabrication. These techniques include plasma activation, modification, functionalization, polymerization and surface interactions. Further discussion is described in Appendix 3.

3.3.3.1 Homogeneous Process

Homogeneous process in dry etching includes pure physical and chemical schemes. It makes etching characteristic simple and easy to study, but some experimental analysis has found that it is hard to fulfil critical dimension at appropriate masking and etching material.

Homogeneous Physical Etching that is also known as pure physical etching involves ion bombardment or ion sputtering where the etching material is non selective but provides directional and anisotropic outcome. This physical method offers almost similar and constant etch rate for different materials. In addition, the volatility of the etch product is not critical where this phenomenon can lead to non selective etching. Otherwise, slow etch rate and electrical damage from ion bombardment would also be contributed from homogeneous physical etching.

Homogeneous Chemical Etching or pure chemical etching provides low voltage, low surface damage and neutral species that are formed in plasma. In most cases, this technique results in isotropic property but it can also be anisotropic in a few cases.

3.3.3.2 Heterogeneous Process

In plasma processing, the term heterogeneous processes include all chemical and physical reactions that occur when fluxes of species are incident on a surface. The interaction of the incident species with the species residing on the surface results in either the gasification of the material or the formation of a new material. Further discussion is given in Appendix 4.

3.3.4 Etch Gases for Dry Etching

Typically etch gases for dry etching are based from three classes which are fluorine (F), chlorine (Cl) and bromine (Br). Chlorine and bromine based etch gases are famous in semiconductor processing application which are commonly used for silicon

and metal layers. Fluorine based etch gases such as SF₆, NF₃, CF₄, C₂F₆ and etc. are often used for silicon, silicon dioxide and silicon nitride etch materials. Moreover, oxygen is often used for cleaning purpose and organics ashing process or as an additive gas in polymer etching. On the other hand, some additive gases such as hydrogen, oxygen and argon are useful agents to improve the process condition when mixing with etch gas. For instance, ion bombardment would increase the etch rate that includes additive gas of argon.

In dry etching process, etch gas influences the material and system requirement. Choices of gas will affect the result and system chamber. Reactions of the selected gas, the appropriate material and the volatility of by-product need to be considered. Some examples for typical materials, gases and products of dry etching are provided in table 3.2.

Table 3.2: Typical etch gases and films of dry etching

Film	Etch Gases	Etch Product
Si	CF ₄ , CF ₄ -O ₂ , CF ₃ Cl, CCl ₄ , SF ₄ -O ₂ , SiF ₄ -O ₂ , NF ₃ , ClF ₃	SiF ₄ , SiCl ₂ , SiCl ₄
SiO ₂	C ₂ F ₆ , C ₃ F ₈ , CF ₄ -H ₂ , CHF ₃	SiF ₄
Si ₃ N ₄	CF ₄ -O ₂ , C ₂ F ₆ , C ₃ F ₈ , CF ₄ -H ₂	SiF ₄
Organics	O ₂ , O ₂ -CF ₄ , O ₂ -SF ₆	CO, CO ₂ , H ₂ O, HF
Al	CCl ₄ , CCl ₄ -Cl ₂ , BCl ₃ , BCl ₃ -Cl ₂ , SiCl ₄	AlCl ₃ , Al ₂ Cl ₆
W, WSi ₂	CF ₄ , C ₂ F ₆ , SF ₆	WF ₆

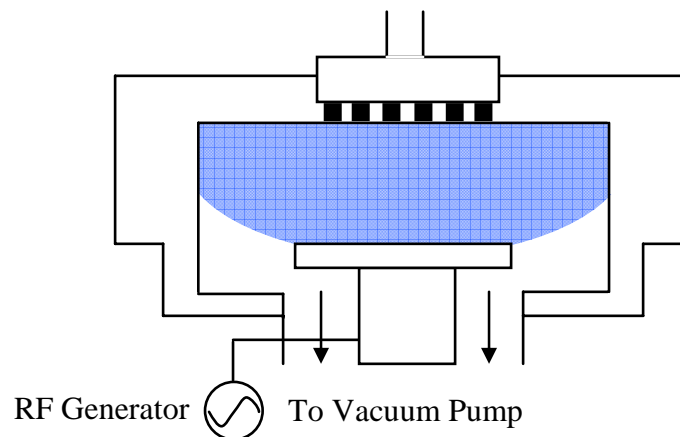
Theoretically, silica etch chemistry in low density plasma RIE plays an important role for SiX₄ etch product where it requires ion current density of about 0.5 mA/cm² and 32 halogen atoms per ion. In low density plasma RIE, neutral species are mainly involved in the etch process. On the other hand, high density plasma requires ion current density of

about 20 mA/cm^2 and 0.8 halogen atoms per ion for SiX_4 etch product and the chemical species are important to volatilize the silica surface.

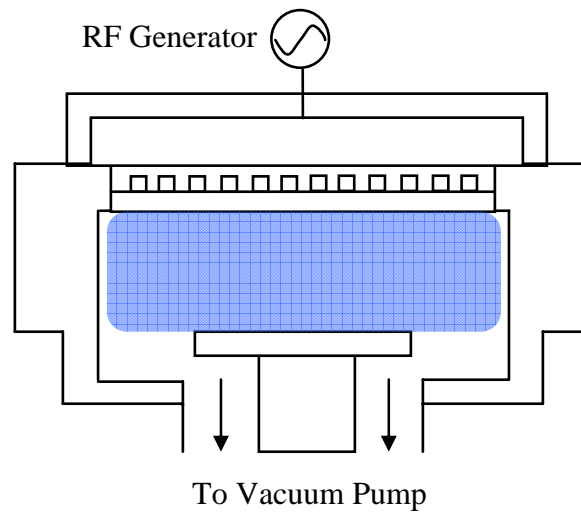
3.3.5 Technology of Dry Etching

Modern very large scale integration (VLSI) processes avoid wet etching and use plasma etching instead. Plasma systems can operate in several modes by adjusting their parameters. There are several categories of Dry Etching that are based on Reactive Ion Etch (RIE), Plasma Etch (PE) and Inductively Coupled Plasma (ICP). Theoretically, dry etching system applies plasma generation method to produce energetic free radicals and neutrally charged, that react at the surface of the wafer where further discussion of this technology is presented in Appendix 5.

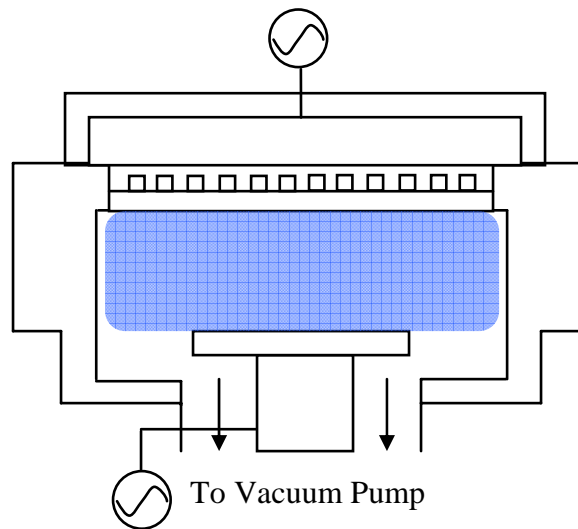
Three of the dry etch systems are illustrated in figure 3.3. During operation, process gases flow through the chamber with the flow rate that is controlled by mass flow controllers (MFCs) and the chamber pressure that is controlled by an automatic throttle valve.



a) Reactive Ion Etching (RIE) System



b) Plasma Etching (PE) System



c) Inductively Coupled Plasma Reactive Ion Etching (ICP RIE) System

Figure 3.3: Schematic diagrams of (a) Reactive Ion Etching (RIE), (b) Plasma Etching (PE) and (c) Inductively Coupled Plasma Reactive Ion Etching (ICP RIE)

3.4 Comparison of Dry and Wet Etching

Dry and wet etching affect material processing of PLC fabrication process. The wet-type is a simple method that usually provides high selectivity with appropriate choices of etchant solutions. It is a well established technology but the exact chemistry is still incompletely understood. As a consequent, the disadvantages of wet etching include several parameters that alter pattern dimensions and prevent line width control such as PR adhesion, isotropic property, over-etching, and liquid surface tension. Narrow features that do not etched uniformly in liquids and somehow mask undercut occurred when etch depth comparable greater than pattern dimension. Additionally, wet etching that implies poor contact between solution and film prevents high aspect ratio features. For instance in the early days, failure analysis was achieved when implementing this technique. However, wet etching is highly isotropic and often results in undercutting and lifting of metal interconnect tracks. Comparisons between dry and wet etching are expressed in table 3.3.

Table 3.3: Characteristics of dry and wet etching

	Wet Etching	Dry Etching
Method	Chemical Solutions	Ion bombardment or Chemical Reactive
Environment and Equipment	Atmosphere, bath	Vacuum Chamber
Advantage	1) Low cost and easy to implement 2) Good selectivity for most materials	1) Capable to defining small feature 2) Anisotropic process 3) Enable control of vertical etch degree 4) Less contamination
Disadvantage	1) Inadequate to defining small feature size as pattern size is smaller than film thickness 2) Potential of chemical handling hazards 3) Wafer contamination issue 4) Isotropic process 5) Mask etch-off problem 6) Undercutting	1) High cost, hard to implant 2) Low throughput 3) Poor selectivity 4) Potential plasma induced radiation damage
Directionality	Isotropic (except for etching crystalline materials)	Anisotropic

Dry etching on the other hand, offers the flexibility to choose either highly anisotropic or isotropic properties, thus enabling a very clean and accurate removal of the layers. This, along with a careful control of selectivity implies that the device can be ‘de-processed’ while preserving the integrity of the overlying circuitry. As a result, more in-depth analysis of the chip is allowed, for example, ICP Dry Etching is beneficial to give less undercut and less corrosion problem for metal features in the structure. In addition, this process has fewer disposal problems compared to wet etching, chemically specific, clean feature, no surface tension issue and inclusive of directional etch where the plasma source consists of applied potential between plasma and wafer.

However, dry etching also has its own disadvantages due to the high cost of operation as a vacuum equipment is required. These include controlling large number of process parameters such as surface geometry of system volume, electrode area, inter-electrode spacing, electrode material, wafer positioning, grids and shutters. Other items

which might influence the characteristics of the discharge are types of gases, flow rates, system conductance, RF power, wafer load and patterning. In addition, dry etching also needs more undercut to remove all mask materials and radiation from plasma that can lead to surface damage.

3.5 Planar Lightwave Circuit Etching Process

In order to form a functional PLC structure on a substrate, it is necessary to etch the silica core layer previously deposited upon the under-cladding. In general, there are two methods of etching processes which are wet etch and dry etch.

Wet etching where the sample is dissolved when immersed in a chemical solution. Dry etching involves where the sample is sputtered or dissolved using reactive ions or a vapour phase etchant. Both of wet and dry etching are useful and suitable for appropriate etch process. Wet etching is the simplest etching technology which using liquid form of etchant to dissolve target sample. All it requires is a container with a liquid solution that will dissolve the sample in all direction. Unfortunately, there are complications since usually a mask is desired to selectively etch the material. One must find a mask that will not dissolve or at least etches much slower than the etch material to be patterned. The result is a pyramid shaped hole instead of a hole with rounded sidewalls with an isotropic etchant.

Wet etching is a simple technology which will give good results if the compatible combination of etchant and mask material to suit the appropriate application. Wet etching

works very well for etching thin films on substrates, and can also be used to etch the substrate itself. The problem with substrate etching is that isotropic processes will cause undercutting of the mask layer by the same distance as the etch depth. Anisotropic processes allow the etching to stop on certain crystal planes in the substrate, but still results in a loss of space, since these planes cannot be vertical to the surface when etching holes or cavities. If this is a limitation for wet etching, it should consider dry etching of the substrate instead. However, the cost per wafer will be 1-2 orders of magnitude higher to perform the dry etching

In case of very small features in thin films which comparable to the film thickness, there may encounter problems with isotropic wet etching, since the undercutting will be at least equal to the film thickness. With dry etching it is possible etch almost straight down without undercutting, which provides much higher resolution.

On the other hand, wet etching will cause undercut and mask peel-off if immersed in wet etchant for long time as for deep silica core etching process. Although wet etching is not suitable for critical etching process, there were applied in thin chromium etching, photoresist (PR) developing and removal. Other than these, wet etching such as hydrofluoric (HF) acid and buffered oxide etch (BOE) are using in silica surface cleaning, measurement and analysis sample preparing process.

ICP dry etching is used in silica core pattern transfer on PC fabrication process. It provide anisotropic etch, better line width control and directional etch due to ion assistance. ICP etch system combined chemical and physical etching which called reactive ion etching (RIE). ICP etch system is also known as Inductively Coupled Plasma Reactive Ion Etch (ICP RIE) system. In ICP RIE processes the wafers sit on the powered

electrode. This placement sets up a negative bias on the wafer which accelerates positively charge ions toward the surface. These ions enhance the chemical etching mechanisms and allow anisotropic etching.

The dry etching process allows for an increased etch rate, as well as a high etch selectivity of fluorocarbon etch gases. The trench formed in the substrate by this process can be made of a larger depth with high reproducibility and good configuration. The sidewall profile angle of the trench is maintained slightly tapered, with a sidewall profile angle of approximately 90 degrees.

3.5.1 Chromium Etch for Metal Masking

Metal masking is one of the pattern transfer step in PLC fabrication process which consists of chromium thin film coating and etching to develop metal hard protective pattern for further silica etching sequence. Wet etching is involved in chromium mask developing where liquid-phase acidic etchant is used to erode unwanted part of this mask by implementing PR pattern transfer.

The Chromium layer is deposited via DC sputter system as dense as possible to form a strong protective mask which is critical for silica etching. The thickness of this layer needs to be a few hundreds nanometer to allow deep silica etching of core layer via ICP.

Wet etching can sometimes produce a slope sidewall profile as the nature of its isotropic characteristic especially in deep or long etching condition. Wet etch sloping phenomena are perpendicular to the etch duration, where the sample that is immersed in

wet etchant for longer time will have higher sloping profile. However, wet etching of the chromium mask is chosen by including acidic chromium etchant as this produces acceptable results with a low cost option where thin chromium hard mask is etched in short duration in stirring step results in acceptable profile.

In research and development stages, chromium wet etching for metal mask pattern transfer is satisfied and it is studied and optimized in the following chapter. It is expected in the future that this technique will replace RIE system to optimise the metal mask's pattern transfer process for commercialized purposes.

3.5.2 Ashing Process

Photoresist (PR) is used in wafer fabrication to transfer a circuit pattern onto the wafer. Once the PR pattern is applied, it must be removed before the next fabrication step. Plasma stripping with dry chemistry is an environmentally friendly way of removing the PR. Wet chemistry may be used, but the danger and expense that are associated with handling wet chemicals are significant where the wet process leaves residues that can interfere with further development.

In plasma ashing, oxygen plasma is mostly used for PR removal and surface cleaning from polymer after etching process. Instead of this, plasma ashing is also used to remove organics prior to SEM and chemical analysis of remaining inorganic. An example is ashing away organic material from filters that miners wear, prior to testing for mineral and asbestos exposure.

3.5.3 Silica Etching

The patterning of dielectrics especially silicon dioxide (SiO_2) that is known as silica, is inherent in the manufacture of modern semiconductor devices. Dielectric etching requires aggressive ion-enhanced, and fluorine-based plasma chemical systems because of higher bond energies between its atoms. Vertical profiles are achieved by sidewall passivation, typically by introducing a carbon-containing fluorine species to the plasma (e.g., CF_4 , CHF_3 , C_2F_6 , C_4F_8). High ion-bombardment energies are required to remove this polymer layer from the oxide, as well as to mix the reactive species into the oxide surface to form SiF_x products. Dielectric etching applications typically rely on the competing influences of polymer deposition and reactive ion etching to achieve vertical profiles as well as etch-stopping on underlying layers [5].

Silica etching process was categorized into two classes which are wet and dry etching. Wet etching consists of using etchant in liquid form which substrates are immersed in a reactive solution (etchant). The layer to be etched is removed by chemical reaction or by dissolution. The reaction products must be soluble and are carried away by the etchant solution. Wet etching is not suitable for small feature size etching as it is isotropic etching, which involved in chemical etching as it will cause undercutting at the etched profile and deteriorates the contrast ratio of the waveguide channels that required for Planar Lightwave Circuit (PLC) applications. Example of wet etching includes: buffered oxide etch ($\text{HF} + \text{NH}_4\text{F} + \text{H}_2\text{O}$) for silicon oxide etching; hot phosphoric acid (H_3PO_4); nitric, HF, acetic acids ($\text{HNO}_3 + \text{HF} + \text{CH}_3\text{COOH} + \text{H}_2\text{O}$) for silicon nitride

etch; Acetic, nitric, phosphoric acids ($\text{CH}_3\text{COOH} + \text{HNO}_3 + \text{H}_3\text{PO}_4$) for aluminium etching.

On the other hand, dry etching was introduced by using gas or vapour etchant which substrates are immersed in a reactive gas (plasma). For dry etching, the layer to be etched is removed by chemical reactions and/or physical means (ion bombardment). The reaction products must be volatile and are carried away in the gas stream. Dry etching is commonly used in semiconductor processing for metal and dielectric with chlorine and fluorine etch gases respectively. Fluorocarbon etch gases such as CHF_3 , C_2H_4 , CF_4 and C_2F_6 are frequently used in silica dry etching [6, 7]. Dry etching with its anisotropic and directional etch, enables more precise control of etch rate and etch profile. Recently, to increase the etch rate without surface contamination, high density plasma etching process using inductively coupled plasma (ICP) system have been developed and applied [8].

Ge, B, P-doped silica glass films are widely used as optical waveguides because of their low losses and inherent compatibility with silica optical fibers. These films were etched by ICP etch system with chromium metal masks, which were patterned by wet chromium etching. [9]

In silica (SiO_2) etching, fluorine (F) atom does not etch SiO_2 without ions. Thus F ions and F neutrals are required in order to etch SiO_2 . The radiation damage that is induced from plasma can be minimized by keeping the energy low and it can also be remedied by annealing.

In practical, dry etching is preferred in silica for its critical dimension to precisely engineer the silica structure prior to the requirement of PLC device fabrication. Additionally, ICP dry etching provides a sophisticated method to the stable and inertly

silica structure. Somehow, wet etching is also involved in the PLC fabrication process for silica surface cleaning. In certain cases, this technique is implemented for developing and removing silica surface due to its advantages in term of lower cost, simplicity and non-critical application.

3.5.3.1 Wet Etch Cleaning Process

In the PLC fabrication process, once after ICP etched surface cleaning is performed hydrofluoric acid and buffered oxide etch (BOE) are used in under-cladding. This is done before deposition process to clean and ensure that the surface condition is good to match the consequence deposited silica layer.

On the other hand, sidewall cleaning with wet etchant is necessary for inspection and measurement. This is done by immersing the diced sample into wet etchant at appropriate duration and performing standard cleaning process sequence before inspection and measurement. By using acid Hydrofluoric (HF) or Buffered Oxide Etch (BOE), the sidewall is cleaned and when inspection by microscope is carried out it shows different tones for different layers of etch depth and thickness.

Wet etching is important in surface cleaning which will change the surface characteristic either hydrophobic or hydrophilic. This is an important method for pre-deposition before and after accomplishing these processes. Etchants media, namely HF or BOE are used for surface cleaning after ICP etch process to remove polymer and sidewall cleaning prior the cross-section inspection.

3.5.3.2 ICP Dry Etching Process

There are several factors that contribute to challenges in implementing dry etching technique. These include the implementation of antireflective coatings and thinner with more sensitive photoresists, the increased aspect ratios needed to meet design requirements, and the additional hard-mask etching steps needed at levels when lithography is unsuitable for patterning. Other factors are increased selectivity requirements especially for those which need contact structures to be self-aligning. Circuit density and performance conditions dictate tighter specifications for line width variations that are permitted across a wafer, micro-loading effects, and device damage. As a result, plasma-etching systems for critical levels are migrating from traditional multi-film, capacitively coupled low-density plasma systems to medium and high-density plasma systems. These elevated schemes employ exotic or highly polymerizing chemical species that are specifically designed for one type of film which is known as Inductively Coupled Plasma (ICP) or Inductively Coupled Plasma Reactive Ion Etch (ICP RIE). Further discussions are stated in Appendix 6 and 7.

3.6 Description and Application of ICP Etch System

Inductively Coupled Plasma (ICP) etch system play an important role in material processing for Planar Lightwave Circuit (PLC) fabrication process. ICP etch system also known as Inductively Coupled Plasma Reactive Ion Etch (ICP RIE) system which use of plasma processing method that combined physical and chemical reaction in etching

process. ICP is a type of plasma source where the energy is supplied by electrical currents which are produced by electromagnetic induction, that is, by time-varying magnetic fields. When a time-varying electric current is passed through the coil, it creates a time varying magnetic field around it, which in turn induces azimuthal electric currents in the rarefied gas, leading to break down and formation of plasma that ready for etching process to begin. Further description of ICP Etch System as described in Appendix 7.

3.6.1 Theory of ICP Etch System

This method applies the implementation of RF current to induce an electric field in plasma region which is primarily tangential to the plasma boundary by inductive element. Further discussion is given in Appendix 8.

3.6.2 Plasma Generation and Characteristic

In general, plasma has three categories of heating modes such as capacitive (E), inductive (H), and helicon wave (W), depending on the external parameters that comprise of pressure, magnetic field, and RF power. Plasma impedances are determined by measurements of amplitudes and phase shift of the current and voltage on the antenna which is considered as a primary coil. The further discussion will be described in Appendix 9.

3.6.3 Etch Profile / Profile Study

Several etch profiles such as ideal sidewall passivation, strong sidewall passivation, bowing, undercutting and notching will be discussed in Appendix 10.

3.6.4 Etch Chemistry and Mechanism

Plasma etching process starts with gas phase dissociation of input gases to become reactive species, and then adsorption of reactive species to the surface of materials to be etched. Reaction of adsorbed species occur with the exposed surface to form volatile product species and lastly, the removal of reaction products and other residue varieties.

Several fluorocarbon etch gases such as CF_4 , C_2F_6 , C_4F_8 , SF_6 and CHF_3 are commonly used in semiconductor and photonics industry. C_2F_6 is quite different from unsaturated fluorocarbons where it produces less CF and CF_2 in constant carbon series and less F in constant fluorine series. These facts come to assumption that less efficient dissociation for C_2F_6 . Theoretically, dissociation of C_2F_6 has higher $[\text{CF}]/[\text{CF}_2]$ ratio and much higher $[\text{F}]/[\text{CF}_2]$ ratio which contribute to less oligomerization and these agree with the basis that C_2F_6 is much less polymerizing than other fluorocarbon gases. Some classification of etch material, plasma chemistry and process parameters are expressed in table 3.4. Furthermore, in-depth etch chemistry and mechanism will be discussed in Appendix 11.

Table 3.4: Classification of etch plasmas and process parameters

Material	Etch Chemistry	Reaction Product
Si	CF ₄ , SF ₆ , HBr, Cl ₂ , NF ₃ , HI	SiF ₄ , SiCl ₄ , SiF ₂ , SiCl ₄ , SiBr ₄ , SiH ₄
SiO ₂ , Si ₃ N ₄	CHF ₃ , C ₄ F ₈ , C ₂ F ₆ , SF ₆ , NF ₃	SiF ₄ , CO, CO ₂
Al	BCl ₃ , HCL, Cl ₂	Al ₂ Cl ₆ , AlCl ₃
W	SF ₆ , CF ₄ , NF ₃ , Cl ₂ , O ₂	WF ₆
	Cl ₂ , O ₂	WOCl _x
Ti, TiN	Cl ₂	TiCl ₄
Polymer	O ₂ , O ₂ /CF ₄ , SO ₂	CO, H ₂ S, CO ₂ , HF, H ₂ , H ₂ O
InP, HgCdTe	CH ₄ /H ₂	In(CH ₃) ₃ , PH ₃ , Cd(CH ₃) ₂
GaAs	Cl ₂ , BCl ₃	Ga ₂ Cl ₆ , AsCl ₃

References

- [1] Williams, K. R., K. Gupta, and M. Wasilik, "Etch Rates for Micromachining Processing– Part II," *Journal of Microelectromechanical Systems*, Vol. 12, No. 6, December 2003, pp. 761–778.
- [2] Thornton, J. A., and D. W. Hoffman, "Stress Related Effects in Thin Films," *Thin Solid Films*, Vol. 171, 1989, pp. 5–31.
- [3] Williams, K., "Etching," in *Properties of Crystalline Silicon*, R. Hull (ed.), London: INSPEC, The Institution of Electrical Engineers, 1999, Chapter 16.
- [4] Williams, K. R., K. Gupta, and M. Wasilik, "Etch Rates for Micromachining Processing– Part II," *Journal of Microelectromechanical Systems*, Vol. 12, No. 6, December 2003, pp. 761–778.
- [5] S. Fang, C. Chiang, D. Fraser, B. Lee, P. Keswick, M. Chang, and K. Fung, *J. Vac. Sci. Technol. A* 14, No. 3, 1092 (1996).
- [6] M. Kawachi, *Opt. Quant. Electron.* 22 (1990) 3911.
- [7] G. Barbarossa, PhD thesis, University of Glasgow, 1993.
- [8] Korczynski, E., *Solid State Technology*, April, 63-73 (1996).
- [9] D. Y. Choi, J. H. Lee, D. S. Kim, and S. T. Jung, "Formation of plasma induced surface damage in silica glass etching for optical waveguides", *Journal of Applied Physics* Volume 95, Issue 12, pp. 8400-8407 (2004).

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

This chapter presents experimental work concerning functions and setup of the system together with the result of Inductively Coupled Plasma (ICP) silica etching process. ICP system is one of the dry-based methods in semiconductor development which is designed for anisotropic materials. It uses turbo molecular pump (TMP) to create a high vacuum environment inside the reactor chamber. The pressure controller is built-in it, to maintain clean and free from contamination condition in the chamber. The vacuum reactor chamber is utilised to induce clean plasma for plasma assisted etching. This will ensure the reliability and repeatability of the machine in addition to the avoidance of contamination which would contribute error in the etching process.

In this thesis, Inductively Coupled Plasma or Inductively Coupled Plasma Reactive Ion Etch (ICP RIE) is mainly studied because of its benefits. These include simple operation, easy to obtain large-size etch uniformity, and independent control capability of the plasma density and the sample bias. The experiment of ICP silica core etching is studied by incorporating etch and additive gases such as Tetrafluoromethane

(CF₄), Hexafluoroethane (C₂F₆) and Argon (Ar). In this experiment, etch characteristics of silica core layer that utilizes the CF₄, CF₄/Ar, C₂F₆ inductively coupled plasma were investigated. The C₂F₆ gas with lower PFC emission than the CF₄ and the SF₆ is one of the widely used gases for the silica etching and for the chemical vapor deposition chamber cleaning.

Etch rate, waveguide profile and the surface morphology were observed as a function of various process variables by employing surface profiler, microscope and scanning electron microscopy (SEM). The surface condition, etch profile and etch depth could also be investigated by incorporating calibrated microscope with capture feature.

As mentioned in the previous chapter, etching is a critical process to the fabrication of Planar Lightwave Circuit (PLC) device as engineered in the core profile to meet the requirement of waveguide channel applications. Thus, the Inductively Coupled Plasma (ICP) arrangement is chosen to drill on the etch parameters.

To obtain an enhancement of silica core etching which is the objective of this thesis, firstly we have to investigate and study the parameters of the Inductively Coupled Plasma (ICP) etch setup. The process parameters studied are inclusive of ICP power, bias power, process pressure, gas flow rate and etch duration that would influence the resultant waveguide profile and surface condition of the sample. However, the temperature control and geometry of the chamber design are also influential to affect the result. But both criteria are not involved in this project due to the fixed chamber geometry and difficulty in controlling temperature.

ICP power and bias power sources with RF frequency of 13.56 MHz are implemented for plasma generation. The ICP RF source is located at the top of the

reactor chamber and the bias RF source is connected to the wafer holder to enable control of negative bias on the substrate. The wafer holder is water cooled at around 20 °C and feed gases are introduced into the reactor chamber by employing mass flow controller. The fluorocarbon etch gas that is either CF_4 or C_2F_6 is used in ICP setup for silica etching process. The reactor chamber was pumped down to a pressure of 10^{-6} Torr by corrosive series turbo molecular pump before feed gases are flowed in. The gas is fed into the chamber where the pressure is maintained at the value that is set by an Automated Pressure Controller (APC) and throttle valve during operation. The schematic of the ICP etching arrangement is depicted in figure 4.1. When the chamber pressure is stable and maintained at the set value, RF power sources can be powered up at an appropriate value and stabilize for about a minute before the commencement of etching process.

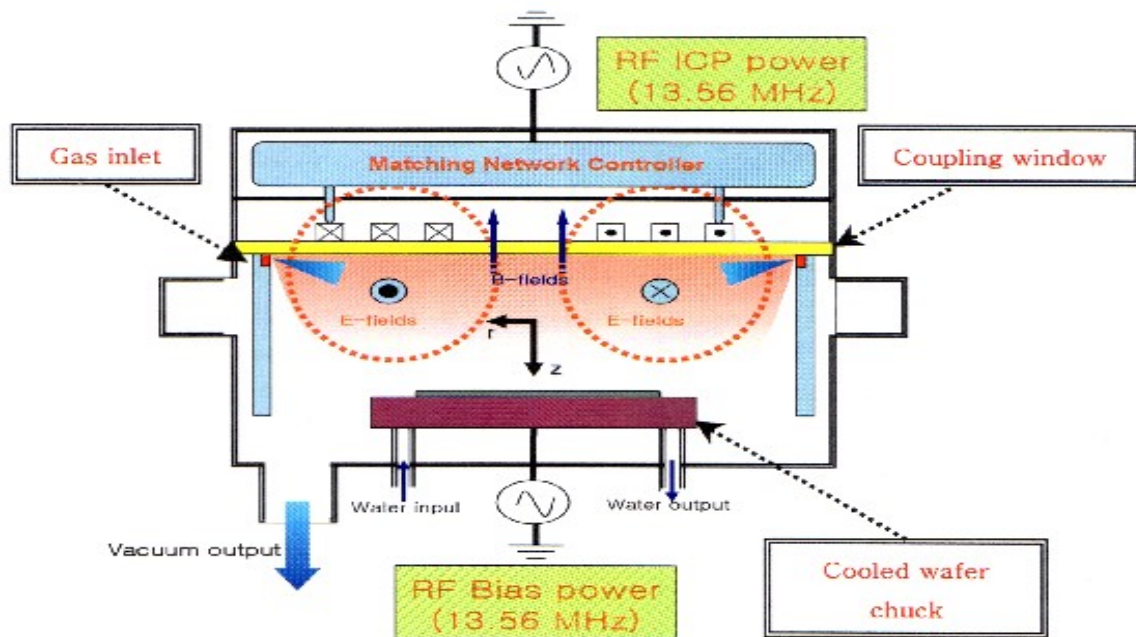


Figure 4.1: Schematic of ICP etching system (Hanvac Corporation)

4.1 Preliminary Work

Preliminary works such as cleaning process, preparation of diluted acid hydrofluoric, microscope setup, surface profiler calibration and standby of ICP etch system are described as the following.

4.1.1 Cleaning Process

The core sample with chromium metal mask is cleaned by a wafer standard cleaning process where it consists of dipping into acetone, methanol, iso-propanol or isopropyl alcohol (IPA) and it is followed by de-ionized (DI) water for 1 to 2 minutes in each step. After the cleaning process, sample with core layer is dried from liquid or moisture with nitrogen gun and oven. These are standard cleaning processes to eliminate the dust and particles that sit on the wafer before the initiation of etching process. Then, the core sample is inspected under microscope to ensure that the sample surface is cleaned and free from contamination. Finally, the cleaned core sample is ready to be loaded into the chamber.

In the case if PR residue occurs, an ashing process is required to completely remove the residue by employing O₂ plasma cleaning. This would avoid contamination of PR residue and prevent from unknown chemical reactions that are involved during operation. The ICP etch system recipe for O₂ ashing is 800 W and 20 W for ICP RF power and Bias RF power, respectively. It is also at 40 sccm O₂ gas flow rate with process pressure of 40 mTorr for 30 minutes.

After the ashing process, the sample is transferred to a load-lock chamber and begins a blank run at appropriate recipes for plasma stability observation. This preliminary process is carried out to ensure the plasma required condition before etching the sample. If the plasma generation is not stable, the reactor chamber needs to be proceeded with mechanical cleaning process. Mechanical cleaning is a basic and simple process but it is a critical procedure that ensures the quality and repeatability of etch results. It would be necessary to proceed, once the etch result is degraded significantly.

4.1.2 Hydrofluoric Acid Dilution

5%, 10%, 20% and 40% diluted hydrofluoric acid (HF) solutions are prepared by mixing Deionised (DI) water with high concentration HF into Teflon containers. Great care have to be taken during dilution and handling of HF where it's extreme corrosive liquid and is a contact poison. In special precaution, do not work without calcium gluconate gel available to treat burn in emergency. Somehow, heavy gauntlet type glove and fume hood are required for handling HF and Buffered Oxide Etch (BOE).

48% of HF is measured with polypropylene measuring cylinder and it is firstly poured into Teflon container. In the next step, DI water is measured according to the dilution ratio where it is poured into the previous Teflon container slowly and carefully to prepare appropriate concentration of HF dilution formula according to the specifications given in table 4.1 and 4.2. From the given HF data sheet, HF specific gravity is 1.16 whereas $G_{HF} = 1.16$ and the related equation is expressed below.

$$\frac{1}{G} \times \frac{X\%}{Y\%} \times V_{Total} = z \quad (4.1)$$

G: Specific gravity

X: Percentage of required dilution

Y: Original percentage of dilution reagent

V_{total}: Total volume of dilution in unit *ml*

z: volume of HF needed in unit *ml*

Table 4.1: Calculation of HF dilution

Density	Y %	V (Y)	X %	V (H ₂ O)	Total Volume	Ratio	
						48% HF	DI water
1.16	48	1.79597701	1	98.20402299	100	1.8	98.2
1.16	48	8.97988506	5	91.02011494	100	9.0	91.0
1.16	48	17.9597701	10	82.04022989	100	18.0	82.0
1.16	48	35.9195402	20	64.08045977	100	35.9	64.1

Table 4.2: Ratio of HF to DI water for several HF concentrations

HF Concentration	48% HF : DI Water
20%	1 : 1.8
10%	1 : 4.6
5%	1 : 10.1
1%	1 : 54.6

4.1.3 Advanced Microscope Setup

The advance microscope setup is a combination of inspection, image capture and measurement functions in one platform. This equipment utilizes an image capture card that is in connection with a computer as illustrated in the diagram below:

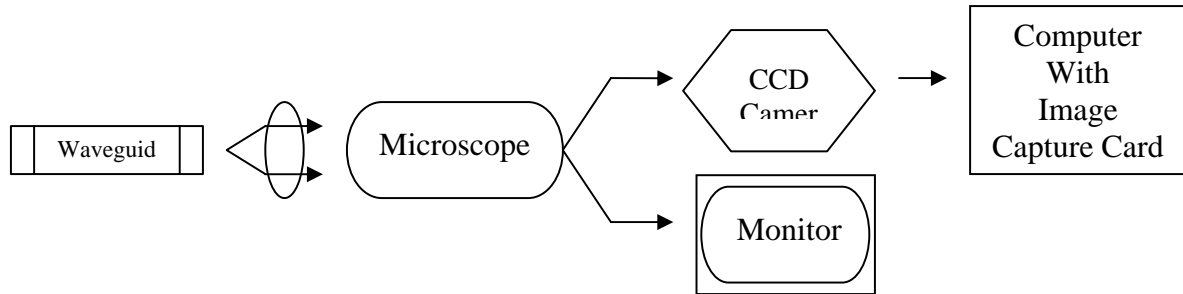


Figure 4.2: Diagram of microscope image capture system

There are many occasions when inspecting the cross sectional profile of a sample is important. Microscope with add-on features and calibrations enable inspection across a selectable view of surface condition in either horizontal or vertical profiles. It displays image of the sample within each selected range of magnification. The resolution and sensitivity of the microscope are selected according to its optics magnification power and brightness. From the inspection of the microscope, we can determine several important parameters in conjunction to the needs of examining the character of the silica core surface and cross section.

The calibrated microscope with image capture feature enabling the approximate measurement of waveguide channel and surface profile. The objective lenses have a

range of 5X, 10X, 20X, 50X and 100X. In addition, microscope has built-in three optional magnification optics that are 1X, 1.5X and 2X. Up to 200 times magnification power could be used to observe surface condition and cross sectional view of waveguide channels.

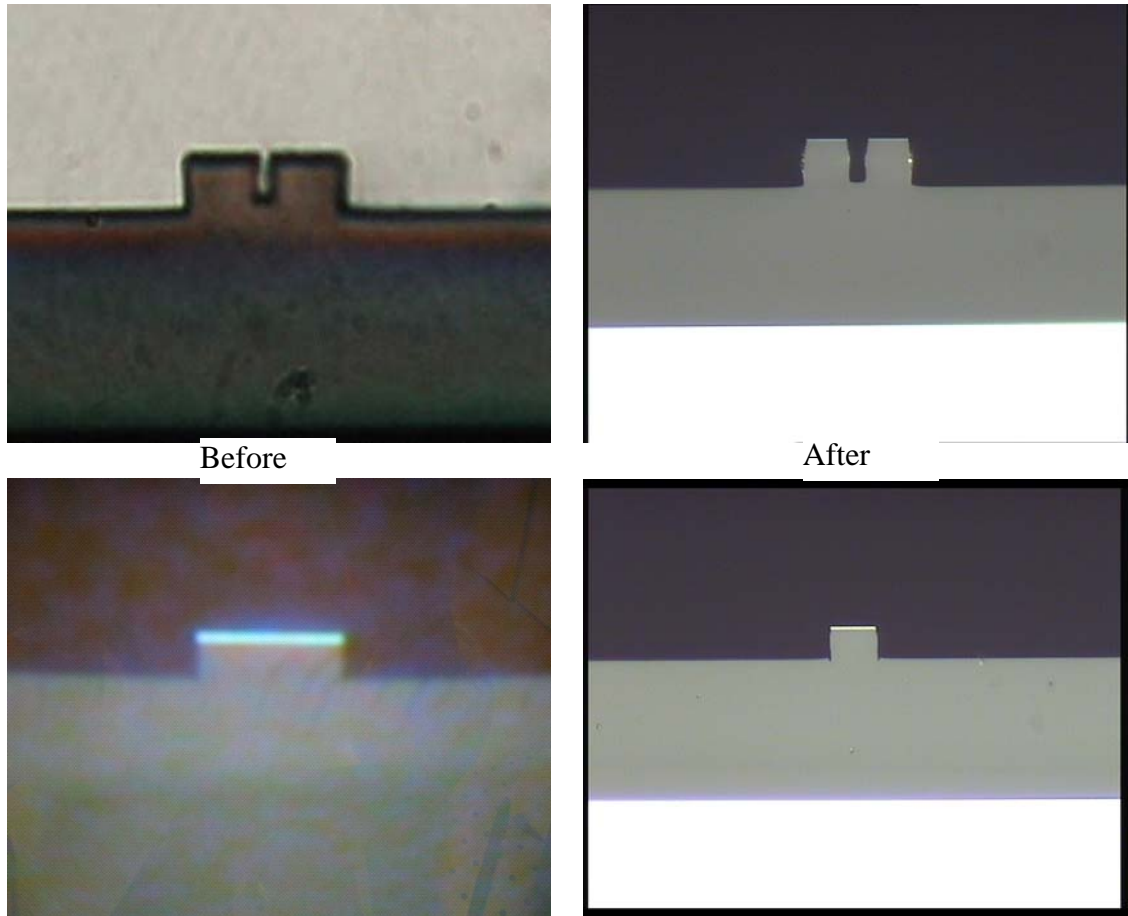


Figure 4.3: Comparison before and after microscope capture system setup

4.1.4 Surface Profiler

Surface profiler is used to measure thickness of chromium metal mask and core etches depth. The full size sample is vacuumed and held by a sample holder, but small diced sample will hold at the sample stage by employing a double-sided tape. Stylus

force is set at appropriate values depending on the sample material and measurement ranges. For instance, harder surfaces like silica layer and chromium mask are measured with higher stylus force. Vice versa, PR pattern is performed by using lower stylus force.

Surface profiler can scan across a selectable range of the sample and it displays the focus image of the sample within each selected range. The resolution and sensitivity of the surface profiler are selected according to its current usage and usually the scanning range is set at 400 micron with 1 measurement point per micron. Surface profiler has a feature that enables the measurement of scan area, width, height and difference between two points. Additionally, their built-in data summaries of four important surface characteristics are Average Height (AVG), Total Indicated Run-out (TIR), Average Roughness (RA) and Cross-sectional Area (Area). There are also other measurement techniques, but they are not related to this project. Micron and nanometer are the units used to describe the etch depth based on the different height of the ridge in the core structure. In addition, surface profiler also enables viewing and positioning. Measurement results can be optionally presented in unit of micron or kÅ. The four surface characteristics are indicated in figures 4.4 to 4.7 overleaf:

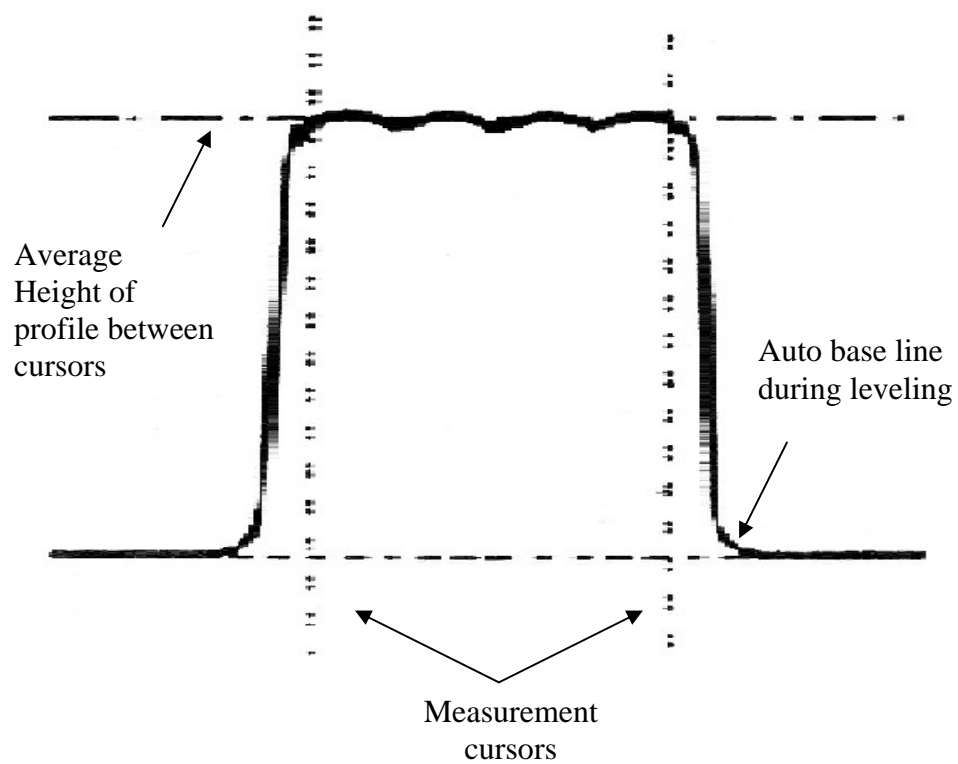


Figure 4.4: Average Profile Height Measurement

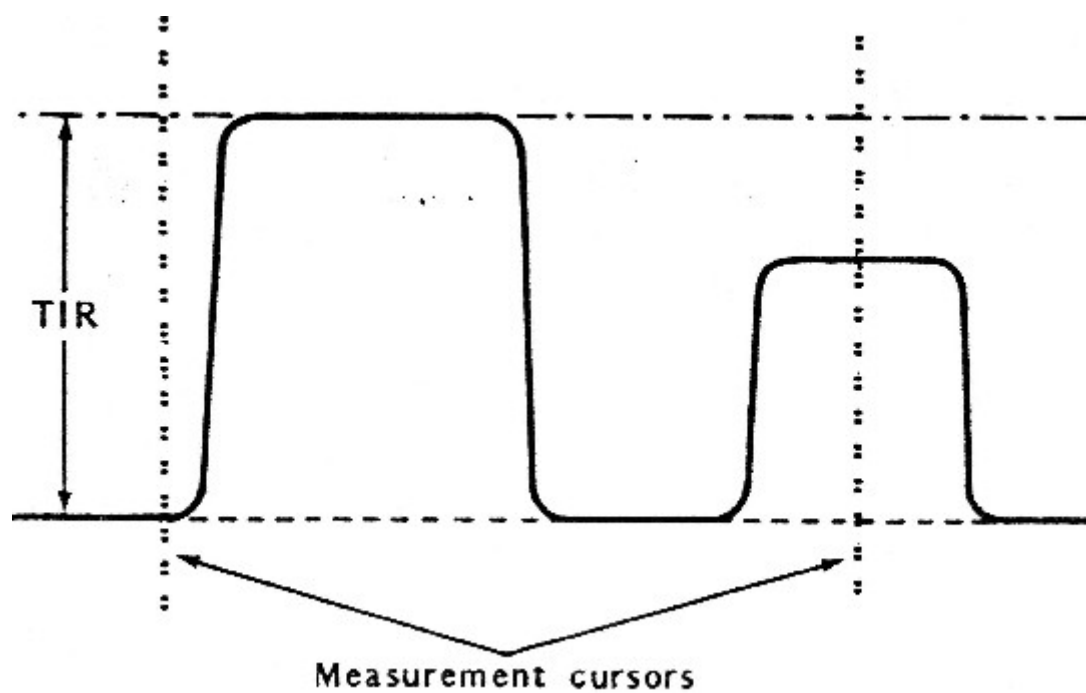


Figure 4.5: Total Indicated Run-out (TIR) Measurement

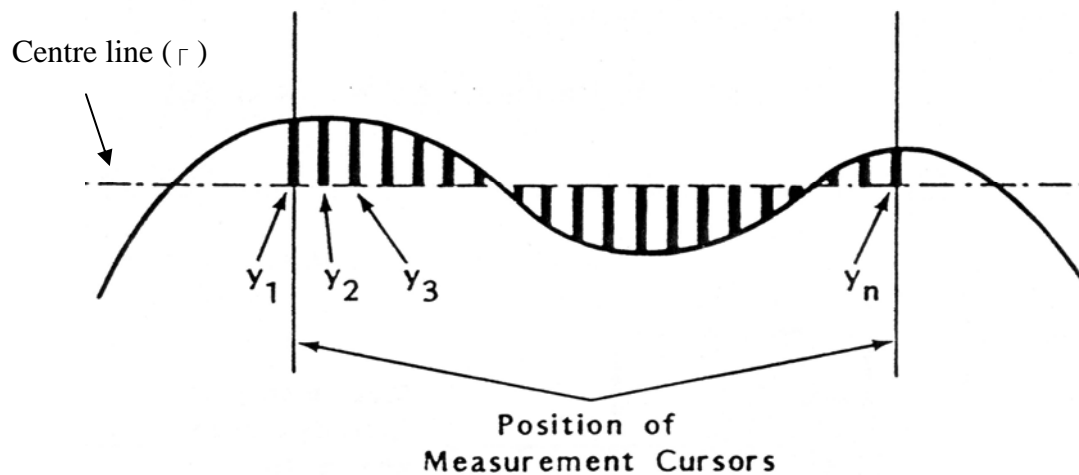


Figure 4.6: Roughness (RA) Measurement

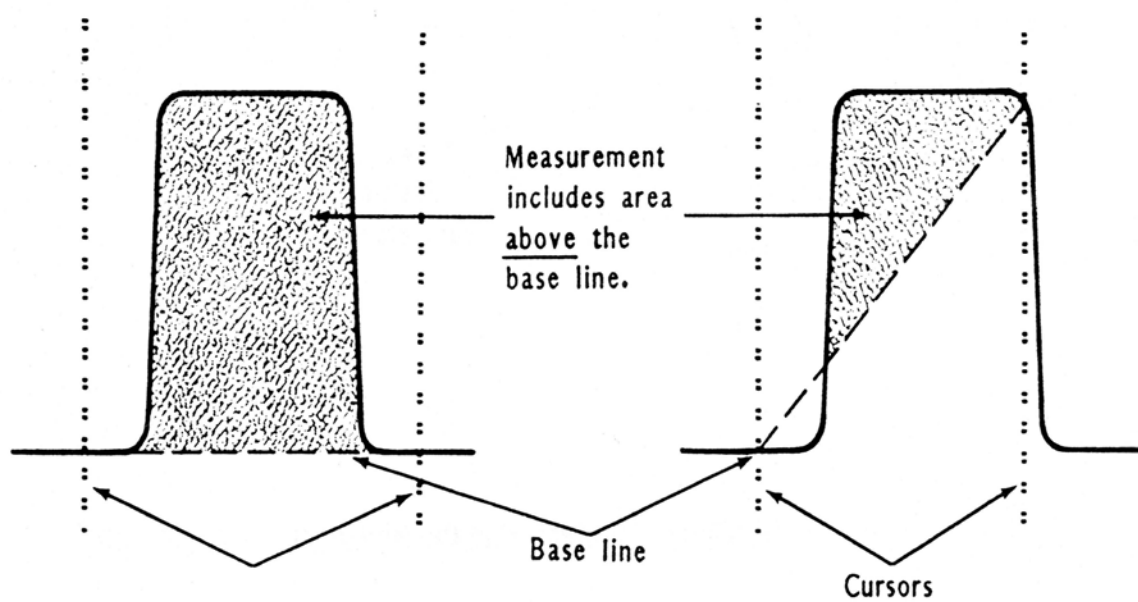


Figure 4.7: Cross-sectional Area (Area) Measurement

4.1.5 ICP Etch System

The ICP etch system is switched on and it stabilizes the system condition for about 10 minutes before operation. Before the switching on procedure, the cooling water system together with pure nitrogen and compressed air are checked and set at appropriate pressures to ensure that the machine works properly under safety environment. In addition, RF power source needs to be warmed up for half an hour in order to ensure plasma stability.

Before etching process, rotary pump's oil level and reactor chamber conditions are checked and pumped down consequently. At the mean time, core sample can be loaded into the load-lock chamber and transferred to the reactor chamber when both chambers are pumped down at a similar pressure. After the reactor chamber is pumped down and stabilized to reach a pressure of 10^{-3} Torr, Turbo Molecular Pump (TMP) can be switched on and stabilized for about half an hour.

Out-gassing is required during reactor's chamber pump down to vacuum condition about 10^{-6} Torr before turn on the RF power source. Etch gas is fed into the reactor chamber and the process pressure is set by an Automatic Pressure Controller (APC) for appropriate etching conditions. Plasma is generated by the output ICP power source when the process pressure of reactor chamber was stable and maintained at appropriate pressure values. At the mean time, bias power could be set and turn on to begin the etching process.

Load-lock chamber and reactor chamber are checked from time to time especially its cleanliness to ensure the etching quality and repeatability. The reactor chamber is cleaned periodically by mechanical cleaning with IPA at the chamber wall and ceramic window. Additionally, argon glow is discharged to induce electron bombardment and

plasma ashing with oxygen for process chamber maintenances. Therefore, any contaminating layer formed on the process chamber during etching process could be eliminated. Otherwise, gas flow is also important and would affect the plasma stability if the gas flow variation is large.

This machine has to be calibrated before operation because plasma or etching parameters affect plasma properties differently from one reactor to another reactor. Parameters which are varied normally include composition of precursors, total gas flow rate, process pressure, etch duration, ICP and Bias powers.

4.2 Methodology

In the beginning of the experiment, wet etch is conducted to study the characteristic of silica wet etching with chromium mask. In wet etching experiment, diluted acid hydrofluoric (HF) and Buffered Oxide Etchant (BOE) were used. The results would be analysed and used as the reference for further comparison between wet and dry etching.

Process parameters such as ICP power, bias power, gas flow rates, and working pressure are controlled by using computer. Chromium was used as etch mask to protect and pattern the waveguide channel for ICP etching process. Fluorocarbon gases CF_4 and C_2F_6 were used as the reactive gases in this system as well. In general, all process parameters cannot be optimized simultaneously. For instance, in the experiment of CF_4 and C_2F_6 etch gases comparison, all parameters are fixed to compare the quality of

results. Etch depth and rate of silica core layer are measured and analyzed by incorporating surface profiler, microscope and SEM.

Scanning electron microscopy (SEM) and microscope with capture feature are employed in surface inspection and depth measurement where the small specimen is prepared by manual dicing. Surface profiler was used to measure depth for the waveguide channel. Microscope with capture feature is frequently used in surface and waveguide profile inspection together with coarse etch depth measurement. Optionally, it is measured by using surface profiler for more precise measurement. Finally, Silica core etch rate was calculated from core etch depth over etch duration after chromium mask etching.

On the other hand, high optical power microscope is required for surface condition and etched profile inspection. From the microscope inspection, we can determine several important parameters in conjunction to the needs of examining the characteristic of the silica core surface and cross section swiftly.

4.3 Experiment

Wet etching experiment was conducted at the beginning stage of the project. Two choices of wet etchants were utilised, namely acid hydrofluoric (HF) and Buffered Oxide Etchant (BOE). 20% of HF and BOE were prepared by adding acid to DI water using Teflon container. In term of duration, the experiment was studied for 20 minutes, 40 minutes and 60 minutes separately for 20% HF and BOE. Surface profiler and microscope were used in etch depth and profile inspection.

However, dry etching is mainly studied in this work by using ICP etch system. In order to investigate the most suitable etch gas for PLC silica etching, CF_4/Ar , CF_4 and C_2F_6 were compared and studied in the first stage. Furthermore, process parameters such as ICP power, Bias power, process pressure and etch gas flow rate were studied by using C_2F_6 etch gas. C_2F_6 was investigated in an effort to improve the etch profile, etch selectivity, etch rate and sidewall verticality. Etch characteristics were studied as a function of ICP power (500-1000 W), Bias power (0-60 W), and process pressure (1-30 mTorr) with etch gas flow rate at the range of 15-60 sccm. Most of the experiments were performed by incorporating 400-500 nm thickness chromium etch mask, deposited by Direct Current (DC) magnetron sputter and patterned by implementing conventional photoresist lithography technique.

The Inductively Coupled Plasma equipment that was employed in this study was composed of two RF plasma sources that were located on top of the chamber and at the bottom of substrate holder. 13.56 MHz RF power was applied on top of the chamber to generate inductively coupled plasma. Separate 13.56 MHz RF power was applied to the substrate to induce negative bias to the substrate where they are called ICP power and Bias power, respectively. The wafer holder is water cooled around 20°C and feed gases were introduced into the reactor chamber by mass flow controllers. CF_4/Ar , CF_4 and C_2F_6 are the feed gases that were introduced to ICP reactor chamber for silica etching process. The reactor chamber was pumped down to a pressure of 10^{-3} Torr by setting a rotary pump and it was further pumped down to a pressure of 10^{-6} Torr by employing a corrosive series turbo molecular pump before feed gases were flowed in. Automated

pressure controller and throttle valve were used to control and maintain the chamber pressure at the set value after etch gas was fed into the process chamber.

Process parameters such as ICP power, bias power, gas flow rates, and process pressure are controlled automatically. Chromium was used as an opaque hard mask to protect and pattern the waveguide channel for ICP etching process. Fluorocarbon gases CF_4 and C_2F_6 were used as the reactive gas in ICP etch system. In experiment of CF_4/Ar CF_4 and C_2F_6 etch gases comparison, all parameters are fixed as to compare the quality of etch profile. Waveguide channel profile, etch depth and etch rate of silica core layer are measured and analyzed by using microscope with capture feature and surface profiler. Optionally, SEM could be used in surface inspection and etch depth measurement more precisely at vertical angle.

In this work, chromium is the mask material that was incorporated as hard mask to pattern silica waveguide channel for about 6 to 8 micron in ICP etching process. In the experiment of CF_4 and C_2F_6 etch gases comparison, process parameters were fixed. Etch result was studied by using the microscope that is explained in figure 4.2.

4.4 Results and Discussion

4.4.1 Experiment of 20% HF Dilution Wet Etching

In the first stage, wet etching experiment was conducted by utilising 20% HF dilution. From the microscope image, disappearance of chromium mask and poor etch profile were observed after immersing into 20% HF dilution for 20 minutes. The

microscope image of before and after HF wet etching is presented in figure 4.8. The waveguide channel height was about 8.8 micron. From the sample surface that is shown in figure 4.9, the chromium mask is totally etched out. The chromium mask was believed to peel-off upon strong undercutting as it was inherently isotropic. As thin chromium mask remained and it's meaningless on further etching for 40 minutes and 60 minutes.

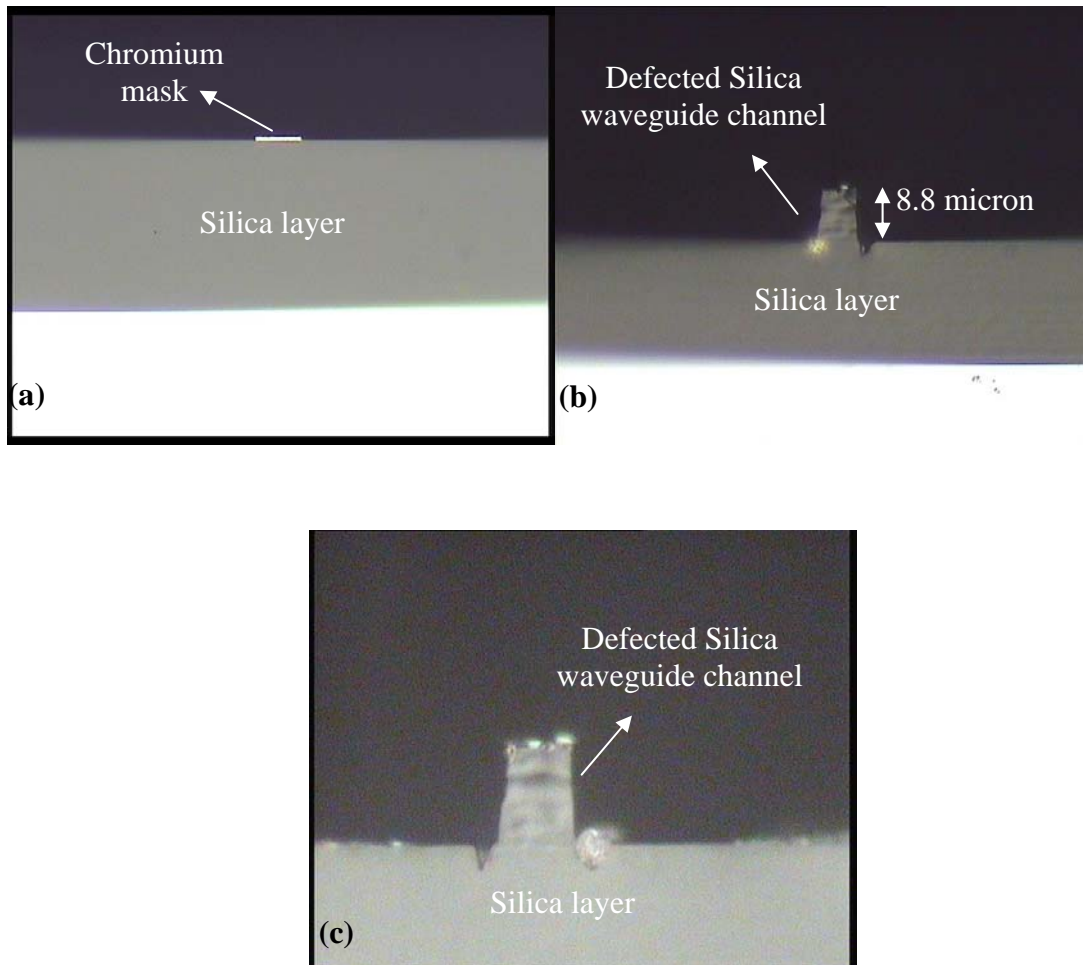


Figure 4.8: Cross sectional view of (a) sample before etch, after 20 minutes wet etching by using HF 20% with (b) 50x microscope magnification and (c) 100x microscope magnification

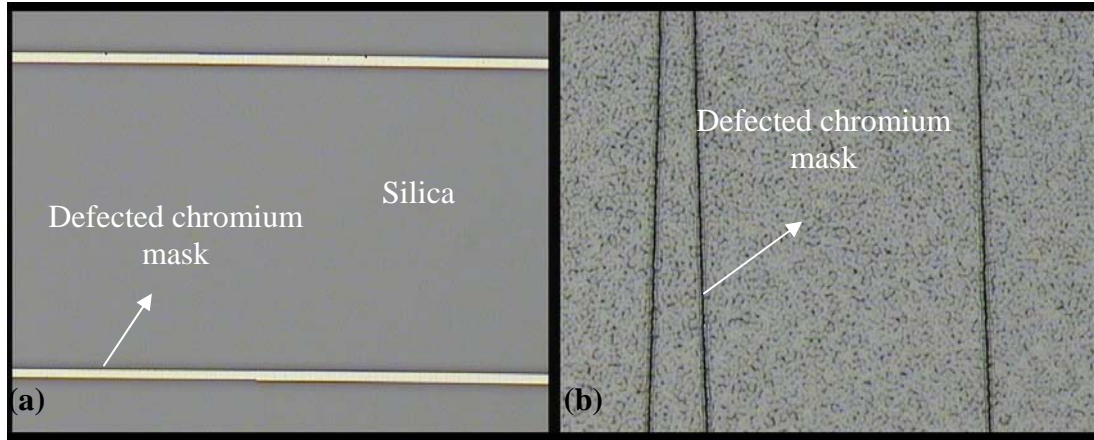


Figure 4.9: Chromium pattern (a) before and (b) after wet etching by utilising HF 20%

4.4.2 Wet Etching of BOE

BOE (6:1) was used in the silica wet etching for 20 minutes, 40 minutes and 60 minutes. The etch profiles for these durations and the original sample profile are expressed in figure 4.10. From this figure, the etch depth was about 0.88 micron and the chromium mask remained, but an undercutting profile occurred after BOE etching was performed for 20 minutes. The undercut profile was more serious due to 40 minutes BOE etching but the chromium mask still remained and an etch depth of about 1.7 micron was measured. After BOE etching for 60 minutes, most of the chromium mask was peeled-off and the waveguide channel height was about 1.8 micron as illustrated in cross sectional view of 4.10 (d) and sample surface in figure 4.11.

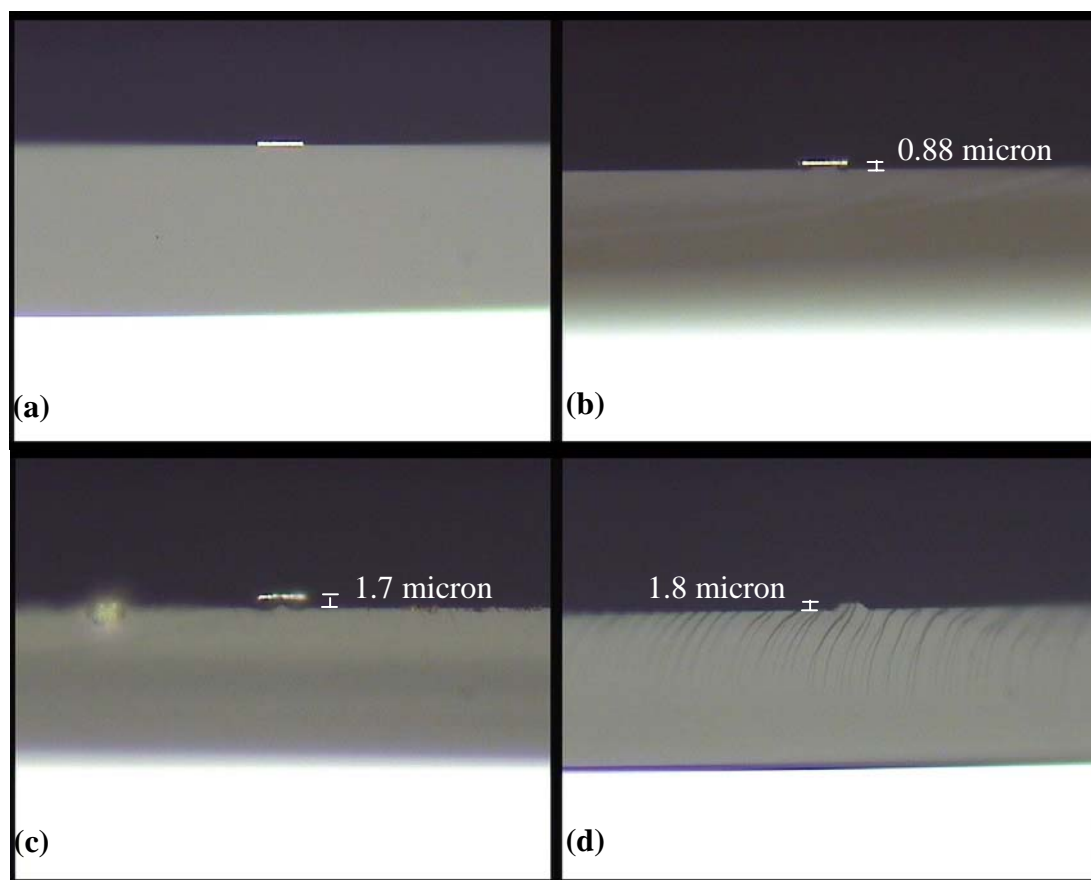


Figure 4.10: BOE wet etching of (a) original silica core layer with chromium mask (b) 20 minutes BOE etching (c) 40 minutes BOE etching and (d) 60 minutes BOE etching

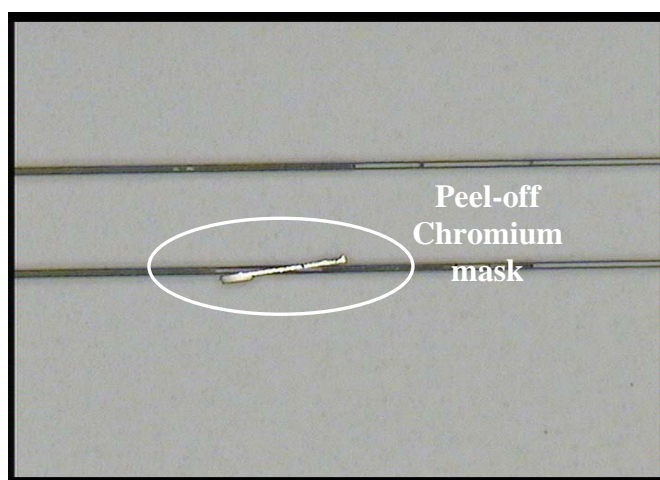
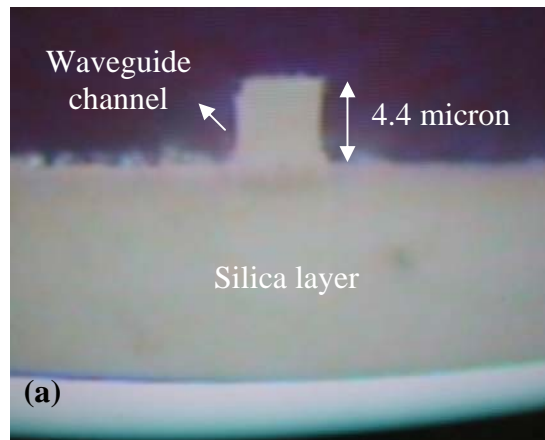


Figure 4.11: Chromium mask peel-off after 60 minutes wet etching of BOE

4.4.3 Comparison of Etch Gases in ICP Silica Dry Etching

Silica dry etching development was conducted via ICP etch system by comparing CF_4/Ar , CF_4 and C_2F_6 . The etch profile was inspected under microscope and the images captured were illustrated in figure 4.12. By employing CF_4/Ar etch gas, the poor waveguide channel without chromium mask was observed. For pure CF_4 etch gas, good etch profile was developed but chromium residue remained after ICP silica etching process. When this was changed to C_2F_6 etch gas, good waveguide channel profile with chromium mask was produced as shown in figure 4.12 (c). From the comparison of three results, it is believed that C_2F_6 was the most suitable etch gas for this assessment.

After ICP etching, the waveguide channel height of about 4.4 micron and 5.1 micron were measured when including etch gases of CF_4/Ar and CF_4 respectively. The suspected chromium mask etch-off happened in both etching process of CF_4/Ar and CF_4 etch gases that are depicted in figure 4.12 (a) and (b). This was prohibited for further etching process to meet the requirement of about 8 micron waveguide channel height.



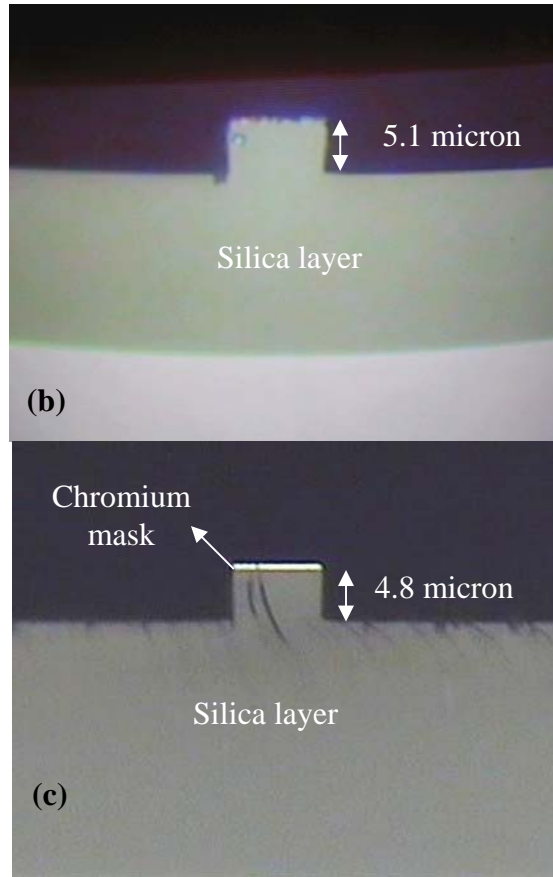


Figure 4.12: ICP dry etching by using mixture etch gases of (a) CF_4/Ar , (b) CF_4 and (c) C_2F_6

4.4.4 Parameters Study of ICP Etching Using C_2F_6 Etch Gas

Results of etch gases that were studied in the previous section, shows that C_2F_6 etch gas enabled to produce rectangular waveguide profile with chromium mask for deeper silica etch. Furthermore, process parameters of ICP etch system were studied and carried on C_2F_6 to optimize the silica etching process as the following. In general, all parameters cannot be optimized simultaneously. Sequentially, running different processes or slowly changing the process parameters as the etch proceeds may be done for the best results.

4.4.4.1 Parameter Study of Bias Power

Table 4.3: Study of etch rate and selectivity by varying Bias power

Bias Power, W	SP(Core)	CrE	ER(Core)	ER(Cr)	Selectivity
0	0.192	0.250	4.800	0.006	0.767
10	1.190	0.250	29.750	0.006	4.760
20	3.766	0.250	94.150	0.006	15.063
30	5.943	0.250	148.575	0.006	23.770
40	7.145	0.250	178.625	0.006	28.580
50	7.877	0.250	196.925	0.006	31.507

In the parameter study of Bias power, other parameters are fixed at 1000 W ICP power, 10 mTorr of process pressure and 50 sccm gas flow rate of C_2F_6 for 40 minutes etching duration. Analysis of this process in table 4.3, shows that silica core etch rate increased proportionally to the bias power. From the surface profiler measurement that is shown in figure 4.13, the silica etching process resulted in the highest etch rate and the highest selectivity of about 197 nm/minute and about 32 respectively at 60 W of Bias power. In term of silica waveguide profile, the Bias power of 30 W produced almost vertical sidewall as illustrated in figure 4.14 (d).

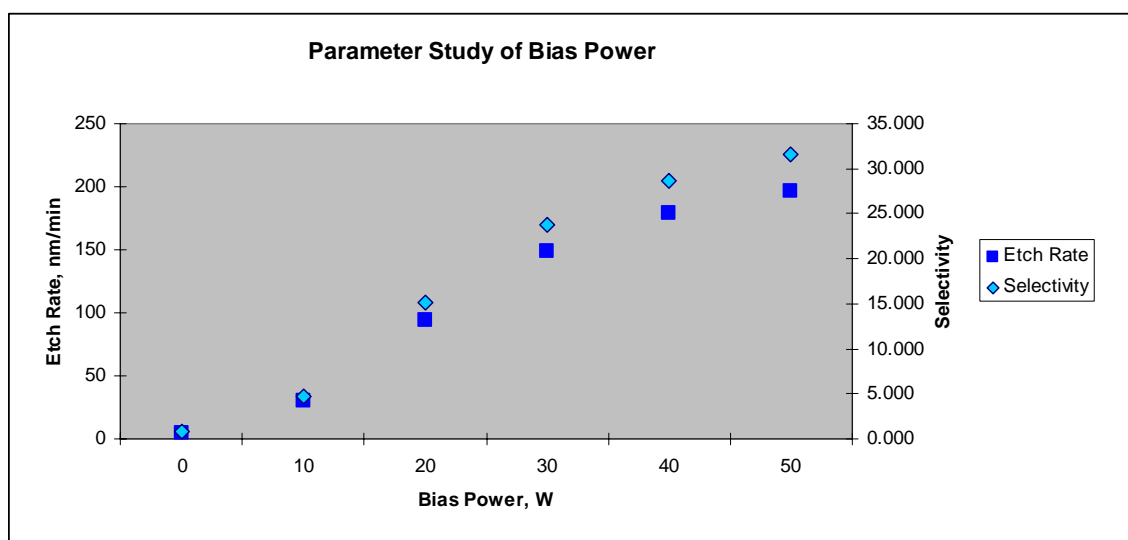


Figure 4.13: Plot of silica core etch rate with varying Bias power with other process conditions fixed at ICP power 1000 W, 10 mTorr process pressure, 50 sccm gas flow rate of C_2F_6 and etch duration of 40 minutes.

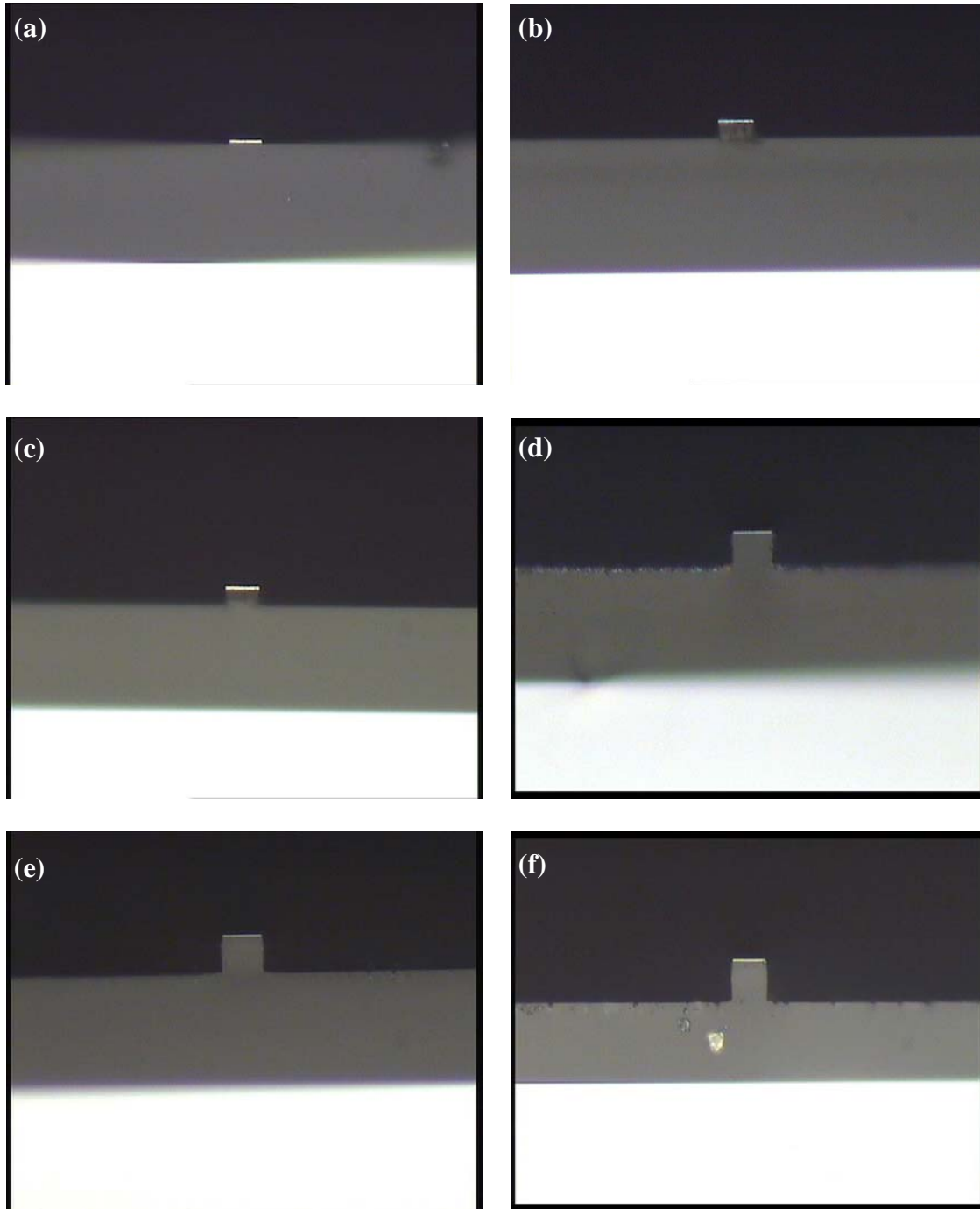


Figure 4.14: Microscope captured images of etched profiles with C_2F_6 at (a) 1000 W-0 W-10 mTorr-50sccm-40min, (b) 1000 W-10 W-10 mTorr-50sccm-40min, (c) 1000 W-20 W-10 mTorr-50sccm-40min, (d) 1000 W-30 W-10 mTorr-50sccm-40min, (e) 1000 W-40 W-10 mTorr-50sccm-40min and (f) 1000 W-50 W-10 mTorr-50sccm-40min.

4.4.4.2 Parameter Study of C₂F₆ Gas Flow Rate

Table 4.4: Study of etch rate and selectivity by varying flow rate of C₂F₆ etch gas

C ₂ F ₆ Gas Flow Rate, sccm	SP(Core)	CrE	ER(Core)	ER(Cr)	Selectivity
15	6.664	0.250	222.00	0.008	26.657
20	6.609	0.250	220.33	0.008	26.437
25	6.443	0.250	214.67	0.008	25.773
30	6.737	0.250	224.67	0.008	26.948
35	6.593	0.250	219.67	0.008	26.373
40	5.746	0.250	191.67	0.008	22.986
45	5.541	0.250	184.67	0.008	22.163
50	5.983	0.250	199.33	0.008	23.933
55	5.533	0.250	184.33	0.008	22.130
60	5.440	0.250	181.33	0.008	21.760

Flow rate of C₂F₆ etch gas that ranges from 15 sccm to 60 sccm was studied in the ICP silica etching processes and other parameters are arranged at 900 W ICP power, 60 W Bias power, 10 mTorr of process pressure for 30 minutes duration. From the analysis of chart that is presented in figure 4.15, application of higher C₂F₆ flow rate slightly decreased the etch rate of the silica core layer. Otherwise, selectivity of silica core layer to chromium mask also declined slowly while increasing in the C₂F₆ flow rate. Process condition at 900 W ICP power, 60 W Bias power, 10 mTorr of process pressure, 30 minutes duration and 30 sccm gas flow rate was performed by utilising the C₂F₆ plasma resulted in the highest etch rate and selectivity of about 225 nm/min and 27, respectively. From the microscope captured image of the waveguide profile, the C₂F₆ flow rate at 40 sccm produced almost vertical sidewall and square waveguide profile as illustrated in figure 4.16 (f).

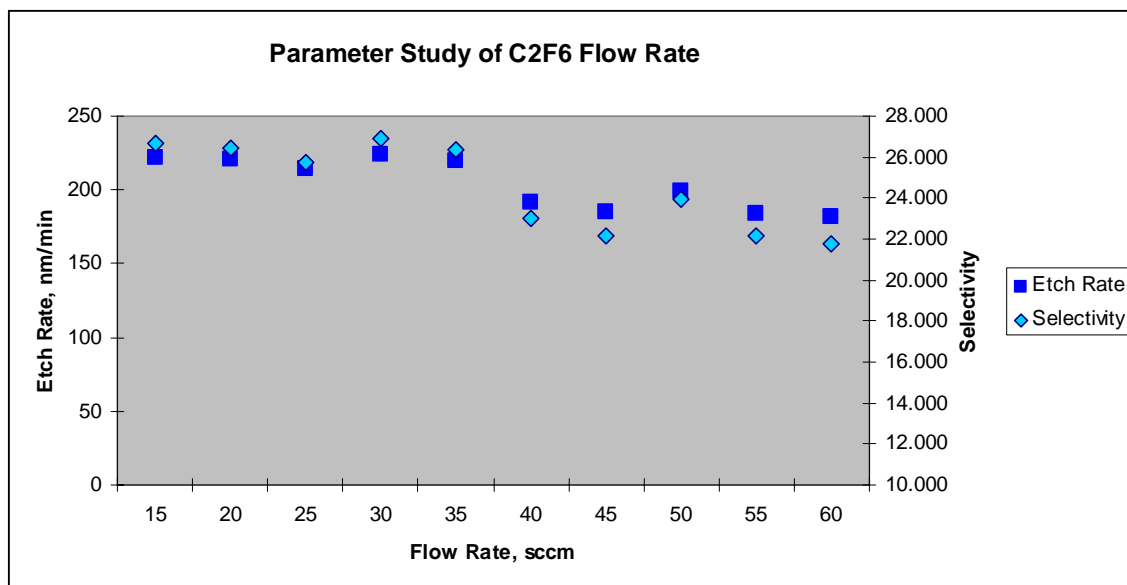
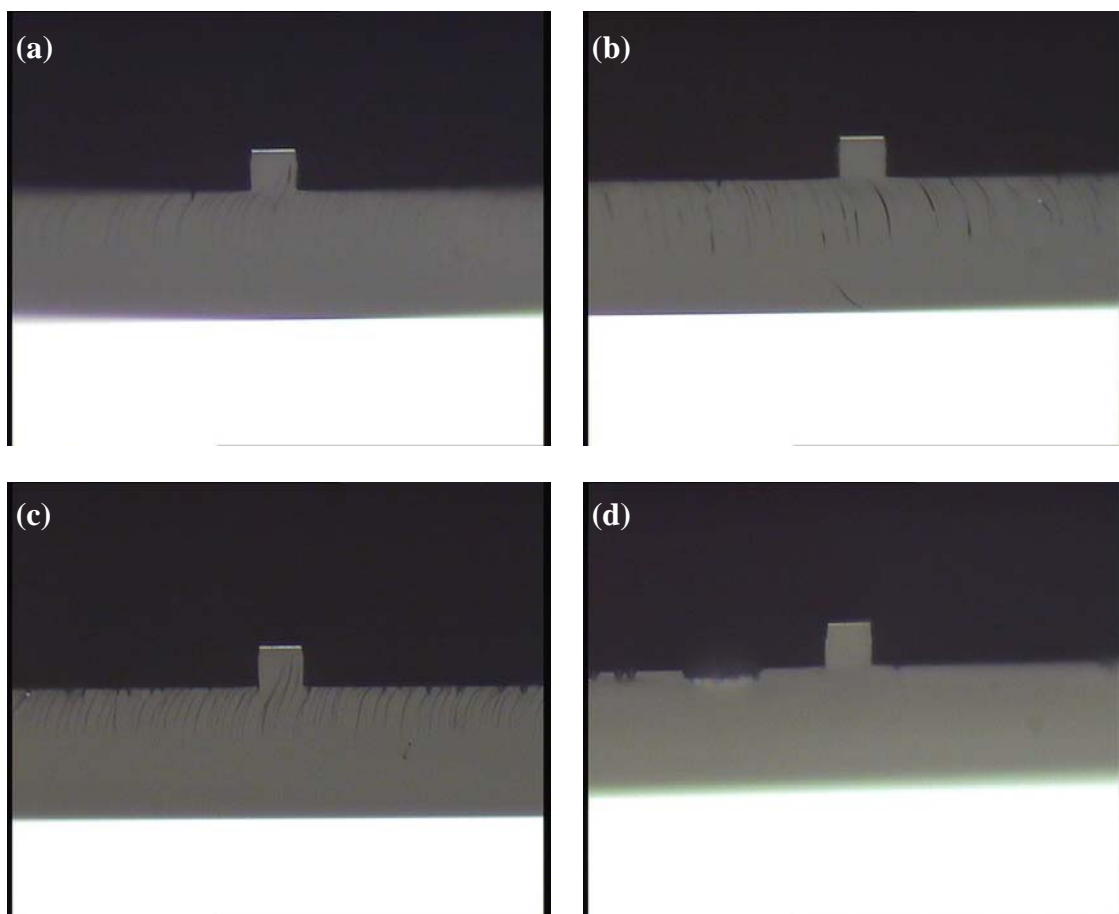


Figure 4.15: Plot of silica core etch rate with varying C₂F₆ gas flow rate with other process conditions set at ICP power of 900 W, 60 W Bias power, 10 mTorr process pressure and etch duration of 30 minutes.



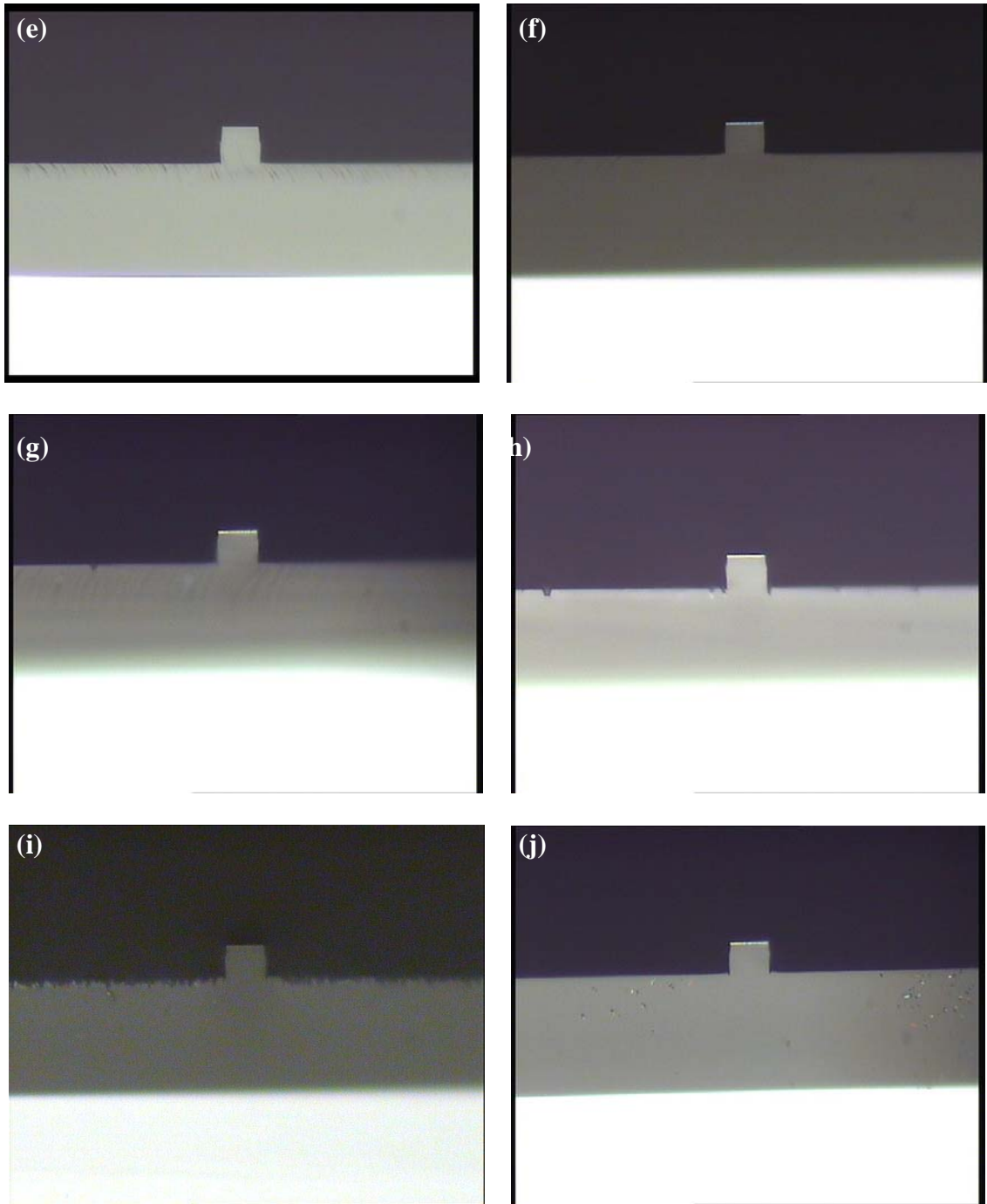


Figure 4.16: Microscope captured images of etched profiles by varying flow rate of C_2F_6 etch gas with process condition as (a) 900 W-60 W-10 mTorr-15 sccm-30 min, (b) 900 W-60 W-10 mTorr-20 sccm-30 min, (c) 900 W-60 W-10 mTorr-25 sccm-30 min, (d) 900 W-60 W-10 mTorr-30 sccm-30 min, (e) 900 W-60 W-10 mTorr-35 sccm-30 min, (f) 900 W-60 W-10 mTorr-40 sccm-30 min, (g) 900 W-60 W-10 mTorr-45 sccm-30 min, (h) 900 W-60 W-10 mTorr-50 sccm-30 min, (i) 900 W-60 W-10 mTorr-55 sccm-30 min and (j) 900 W-60 W-10 mTorr-60 sccm-30 min.

4.4.4.3 Parameter Study of Process Pressure

Table 4.5: Study of etch rate and selectivity by varying process pressure

Process Pressure, mTorr	SP(Core)	CrE	ER(Core)	ER(Cr)	Selectivity
1	6.575	0.250	219.33	0.004	26.300
5	6.653	0.250	221.67	0.007	26.610
10	6.593	0.250	219.67	0.006	26.373
15	5.871	0.250	195.67	0.005	23.485
20	4.425	0.250	147.67	0.009	17.700
25	3.683	0.250	122.67	0.008	14.733
30	3.354	0.250	111.67	0.007	13.415

In this study, pressure of process chamber that ranges from 1 mTorr to 30 mTorr was maintained and studied in the ICP silica etching processes. Other process parameters are determined at 900 W ICP power, 60 W Bias power and 35 sccm of C_2F_6 flow rate for 30 minutes etching duration. From the analysis of the chart that is plotted in figure 4.15, higher process pressure resulted in better sidewall profile, but lower etch rates and selectivity were obtained. The decreasing of etch rate was suspected caused by inclining of passivating, or buffering ion/molecule which affected at large mean free path while increasing the process pressure. Otherwise, increase of process pressure would increase the residence time of feed gases especially for those with heavier molecules hence lower the silica etch rate. The decreasing in selectivity was mainly affected by drastic decrease in silica etch rate from 10 mTorr to 30 mTorr since the chromium mask etch rate decreasing simultaneously. From the results given in table 4.5, process condition at 900 W ICP power, 60 W Bias power, 5 mTorr of process pressure, 30 minutes of etching duration and 35 sccm gas flow rate that incorporated the C_2F_6 plasma resulted in the highest etch rate and selectivity of about 222 nm/min and about 27, respectively. From the comparison of waveguide profiles that was captured from the microscope, process

pressure at 20 mTorr produced square waveguide profile and almost vertical sidewall profile as illustrated in figure 4.18 (e). During the ICP silica etching, the status of plasma generation was observed and it was found that the most stable plasma condition at the lowest process pressure was at 10 mTorr.

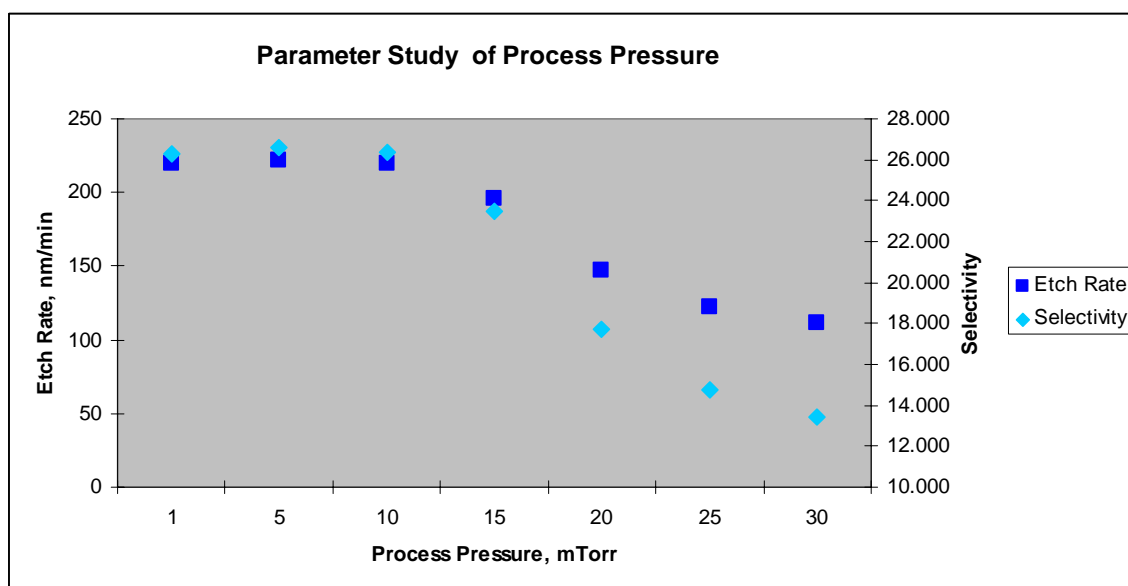
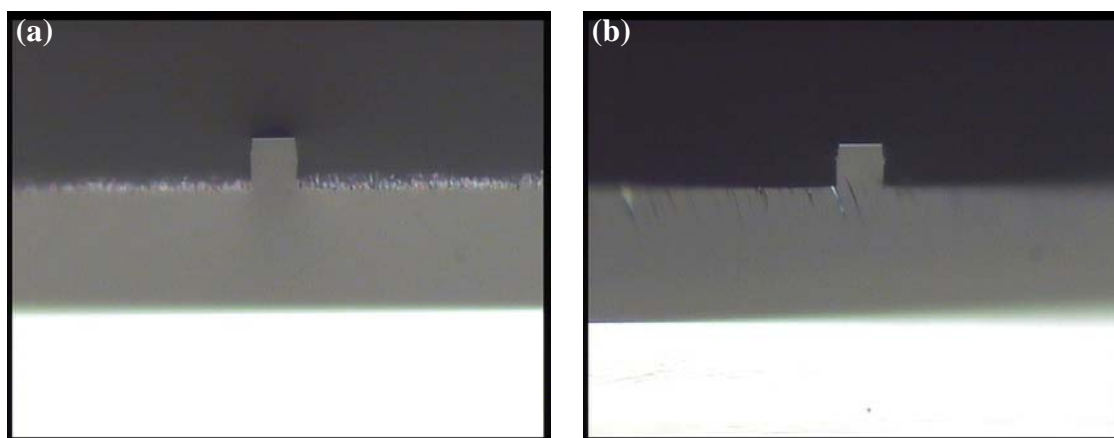


Figure 4.17: Plot of silica core etch rate with varying process pressure with other process conditions fixed at ICP power 900 W, 60 W Bias power, 35 sccm gas flow rate of C_2F_6 and etch duration of 30 minutes.



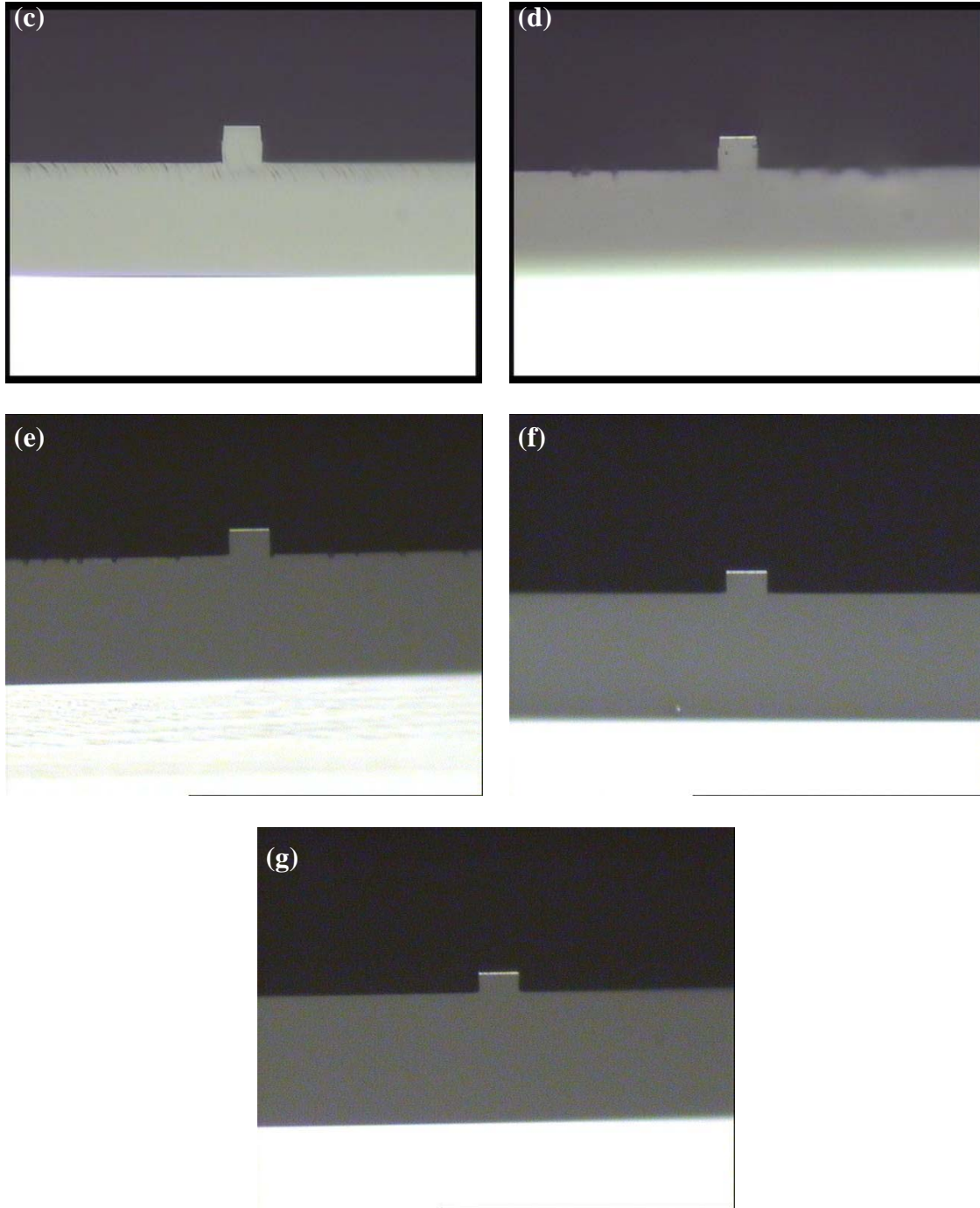


Figure 4.18: Microscope captured images of waveguide profiles with C_2F_6 etch by varying process pressure at process condition as (a) 900 W-60 W-1 mTorr-35 sccm-30 min, (b) 900 W-60 W-5 mTorr-35 sccm-30 min, (c) 900 W-60 W-10 mTorr-35 sccm-30 min, (d) 900 W-60 W-15 mTorr-35 sccm-30 min, (e) 900 W-60 W-20 mTorr-35 sccm-30 min, (f) 900 W-60 W-25 mTorr-35 sccm-30 min and (g) 900 W-60 W-30 mTorr-35 sccm-30 min.

4.4.4.4 Parameter Study of ICP Power

Table 4.6: Study of etch rate and selectivity by varying ICP power

ICP Power, W	SP(Core)	CrE	ER(Core)	ER(Cr)	Selectivity
500	3.134	0.05	104.33	0.002	62.683
600	3.818	0.08	127.33	0.003	47.719
700	5.086	0.13	169.67	0.004	39.122
800	5.326	0.18	177.67	0.006	29.588
900	6.593	0.25	219.67	0.008	26.373
1000	6.790	0.35	226.33	0.012	19.400

ICP power in a range from 500 W to 1000 W was studied in silica etching process with fixed parameters at 60 W Bias power, 10 mTorr of process pressure and 35 sccm flow rate of C_2F_6 etch gas for 30 minutes duration. Analysis of the results are given in table 4.6, where for ICP power at 1000 W, 60 W Bias power, 10 mTorr of process pressure and 35 sccm flow rate of C_2F_6 etch gas for 30 minute duration resulted in the highest silica etch rate of about 226 nm/min. In addition, the highest selectivity of about 63 was achieved at 500 W of ICP power.

From the chart that is plotted in figure 4.19, we found that silica etch rate was linearly proportional to the ICP Power and inversely proportional to the selectivity of silica to chromium mask. Applications of higher ICP power resulted in higher etch rates, but a slope was obtained as a result of enhanced mask erosion. The declining of etch selectivity was affected by the increasing of ionization power at higher ICP power.

From the microscope captured images, waveguide profiles at variable ICP powers were compared. In term of etched silica waveguide profile, ICP powers at 500 W and 600 W produced square waveguide profile and almost vertical sidewall as illustrated in figure

4.20 (a) and (b). The etched sample at 600 W ICP power resulted in higher etches rate compared to 500 W ICP power but higher selectivity was achieved at 500 W ICP power.

The status of plasma generation was observed and it was found that the most stable C_2F_6 plasma condition at the lowest ICP power was at 500 W. At the same condition, 400 W ICP power induced a slightly consistent C_2F_6 plasma stability whereas the flickering occurred during the ICP silica etching process._

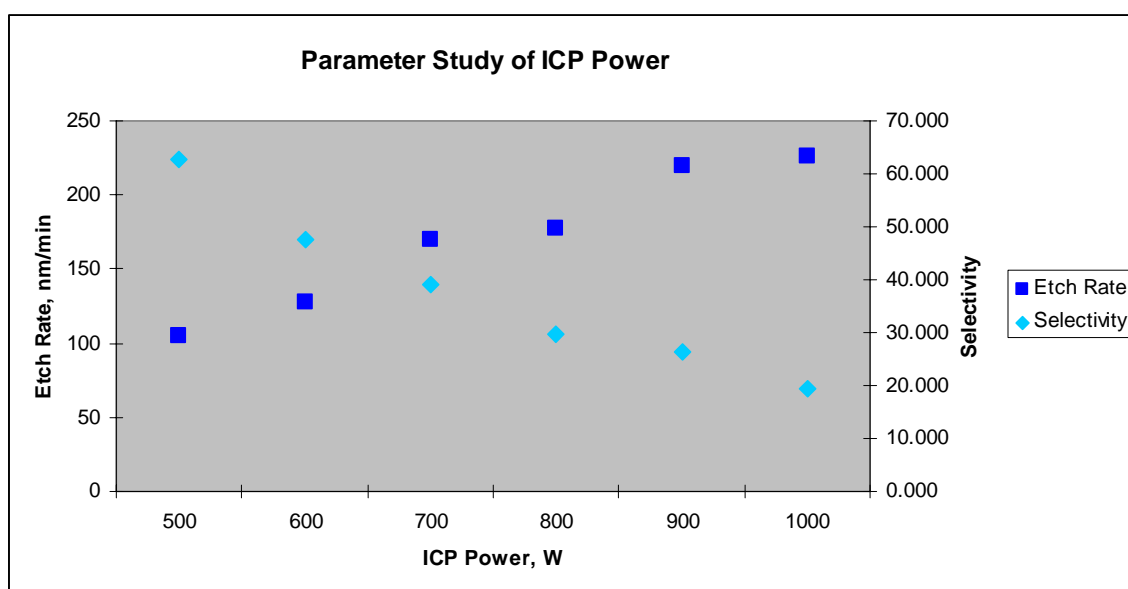
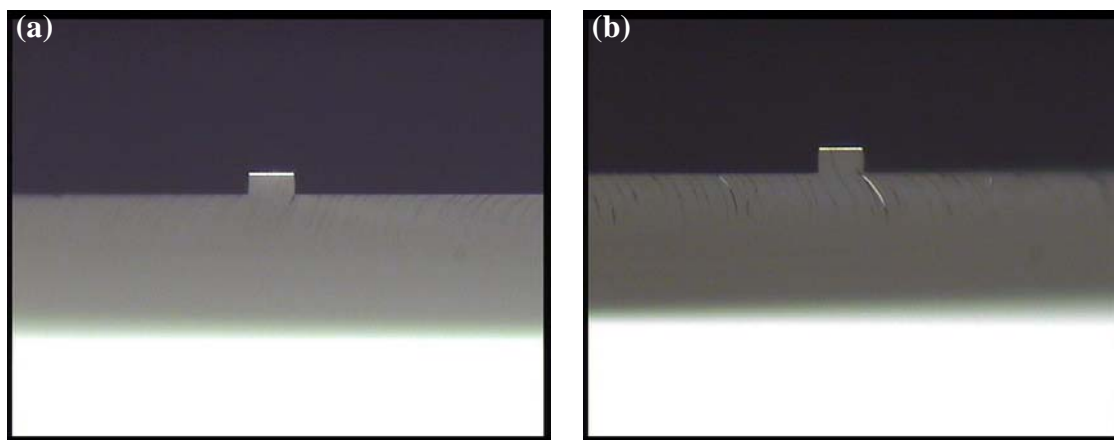


Figure 4.19: Plot of silica core etch rate with varying ICP powers from 500 W to 1000 W. Other process parameters determined at Bias power 60 W, 10 mTorr process pressure, 35 sccm gas flow rate of C_2F_6 and etch duration of 30 minutes.



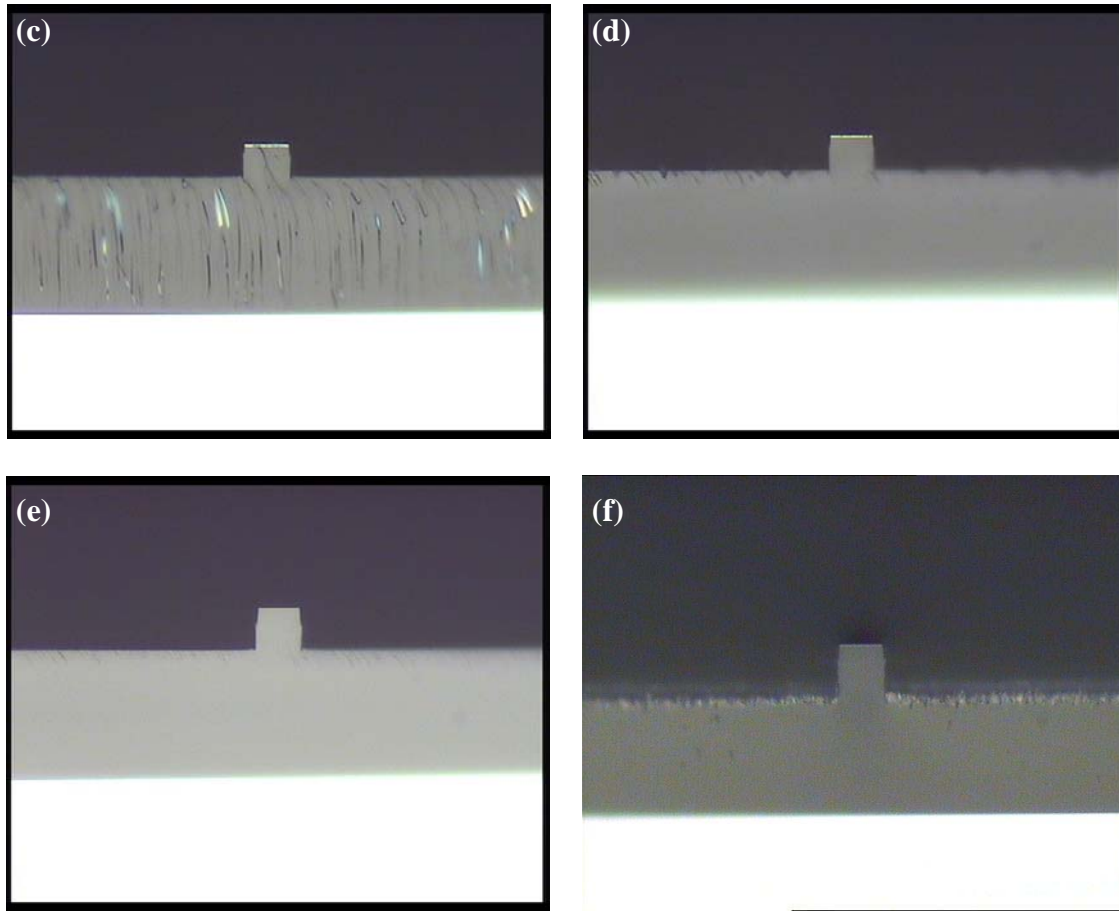


Figure 4.20: Microscope captured images of waveguide profiles after silica etching with C_2F_6 etch gas by varying ICP powers at process condition of (a) 500 W-60 W-10 mTorr-35 sccm-30 min (b) 600 W-60 W-10 mTorr-35 sccm-30 min, (c) 700 W-60 W-10 mTorr-35 sccm-30 min, (d) 800 W-60 W-10 mTorr-35 sccm-30 min, (e) 900 W-60 W-10 mTorr-35 sccm-30 min and (f) 1000 W-60 W-10 mTorr-35 sccm-30 min.

4.5 Problems and Solutions

One of the main problems of ICP etch system is plasma instability which lead to degrading and abnormal etching results. Solution is found while troubleshooting the

interference and grounding the RF power. However, the problem is encountered by extended wiring to the ground and interference isolation by the aluminium foil.

Secondly, turbo molecular pump (TMP) will over heat if high process pressure is set for long etch durations. As a result, the pressure is limited to certain values at appropriate durations and usually the limits are no more than 50 mTorr during the operation.

CHAPTER 5

CONCLUSION & FUTURE WORK

5.1 SUMMARY AND CONCLUSION

In this project, silica etching was studied either in wet- or dry-based mechanisms. Dry etching is chosen as the most compatible process to accomplish the requirement in submicron micromachining and small feature size structures especially in the silica material. Its vertical sidewall, repeatability, directionality and uniformity are well suited to the need of this process.

ICP silica etching is best suited for the needs of etching in Planar Lightwave Circuit Fabrication. The major changes in chemical gas and mixture gases from CF_4/Ar to CF_4 and finally to C_2F_6 has moved forward the etching progress and improvement. The refinement of the etching condition is achieved by fine tuning the parameters such as ICP power, bias power, etch gas flow rate and process pressure. The profiles of the waveguide core channel and remaining chromium mask are the main focus prior to produce good quality optical waveguide channels. The selectivity, etch rate and duration

are important factors on fine tuning to optimize the process condition, yield, quality and efficiency of the system and end products.

Firstly, and the main criterion to carry out on silica dry etching is the waveguide profile of silica core pattern which must be straight and square. Secondly, selectivity and etch rate of silica core layer are considered to meet the appropriate depth along with the squared waveguide profile. In the mean time, thickness of chromium mask will vary for appropriate operating conditions. Requirements with compatible thickness of chromium mask of about 300 nm to 600 nm on ICP silica dry etching incur appropriate etch depth.

In the experimental part, silica etching was firstly conducted with two wet-based solutions which incorporated hydrofluoric acid (HF) and buffered oxide etch (BOE). 20% HF silica etching resulted in much higher etch rate compared to that with BOE, but both processes produced poor and defect waveguide profiles. As a conclusion, wet etching neither in HF nor BOE was suitable for silica waveguide patterning on Planar Lightwave Circuit fabrication as the chromium mask peel-off and isotropic in both implementations.

Alternatively, silica dry etching was conducted via ICP etch system after the failure in wet etching. In the first stage, a comparison of etch gases in ICP-based process was studied. From the microscope captured images, CF_4/Ar and CF_4 plasma etching produced good and rectangular shape waveguide profiles at the etch depth of about 4.4 micron and 5.1 micron, respectively. However, the chromium mask was totally etched-off and the insufficient etch depth without the chromium would inhibit further etching process. In contrast, when using C_2F_6 etch gas instead of former gases, the chromium mask remained. The microscope image showed improved etch profile with high selectivity and the channel height was about 4.8 micron with thick chromium mask

remained. This would allow further etching to meet the depth requirement of about 8 micron. The improved profiles and selectivity indicated that C_2F_6 gas was preferable gas instead of CF_4/Ar and CF_4 in PLC fabrication because it resulted in better selective etch and good profiles. Furthermore, parameters such as ICP power, Bias power, process pressure and flow rate of C_2F_6 etch gas were also studied.

In Bias power study, silica core etch rate increased proportionally to the Bias power at set parameters of 1000 W ICP power, 10 mTorr of process pressure and 50 sccm flow rate of C_2F_6 gas in 30 minutes period. Bias power at 60 W resulted in the highest etch rate and the highest selectivity of about 197 nm/minute and 32, respectively. In term of waveguide profile, Bias power at 30 W produced good waveguide channel and almost vertical sidewall.

Furthermore, flow rate of C_2F_6 gas was studied at 900 W ICP power, 60 W Bias power and 10 mTorr of process pressure in 30 minutes of duration. The incorporation of higher C_2F_6 flow rate slightly decreased the etch rate and selectivity of silica core layer to chromium mask. The 30 sccm flow rate of C_2F_6 gas resulted in the highest etch rate and selectivity of about 225 nm/min and 27, respectively. A good waveguide profile was produced at 40 sccm flow rate of this gas.

In the next assessment, the process pressure in the range of 1 mTorr to 30 mTorr was studied. Fixed parameters were 900 W ICP power, 60 W Bias power, 35 sccm flow rate of C_2F_6 gas and 30 minutes of duration. The higher process pressure resulted in better sidewall profiles, but lower etch rates and lower selectivity were obtained where these were due to the suspected increase in heavier passivating ion/molecule and longer ion/molecule residence time at the sample surface. The highest etch rate and selectivity of

about 222 nm/min and about 27, respectively were obtained at process pressure of 5 mTorr. The process pressure at 20 mTorr resulted in square waveguide profile and almost vertical sidewall profile.

The range from 500 W to 1000 W ICP powers were studied at specified parameters of 60 W Bias power, 10 mTorr of process pressure and 35 sccm of C_2F_6 flow rate for 30 minutes duration. Silica etch rate was found to be linearly proportional to the ICP Power and inversely proportional to the selectivity of silica to chromium mask. The maximum etch rate of about 226 nm/min and the highest selectivity of about 63 were obtained at ICP powers of 1000 W and 500 W, respectively. At 500 W and 600 W ICP powers, good and vertical waveguide profiles were obtained but these were compensated with low etch rates of 104 nm/min and 127 nm/min, respectively.

The present work represents a step towards better understanding of the interaction between system parameters such as ICP Power, Bias Power, etch gas flow rate, process pressure, etch duration and hence towards optimizing these parameters. It aims to draw attention to the importance of these parameters for a faster and better channel profile in silica core layer etching. As a conclusion, in conjunction with sufficiently high selectivity, high yield and significantly good waveguide profile with vertical sidewall the optimum etch rate of about 192 nm/min was obtained. This was achieved at ICP power of 900 W, 60 W of Bias power, 10 mTorr of process pressure and 40 sccm flow rate of C_2F_6 gas for 30 minutes duration.

After the study of dry etching process, we noticed that silica dry etching which was conducted via Inductively Coupled Plasma (ICP) system gave the most promising results. As the conclusion, ICP RIE was the most effective and compatible silica etching

for Planar Lightwave Circuit fabrication. This was because it accurately produced and engineered the silica core structure that was the most critical requirement for low loss waveguide channels.

5.2 Future Work

5.2.1 In-Situ Diagnostic

The in-situ diagnostics are suggested for future work to improve and study the system for better understanding of the plasma processing. This method can also meet more stringent constraints required by high complexity and more advance PLC fabrication such as greater channels of beam splitter, AWG, Add/Drop Multiplexer and etc. Some of the in-situ instruments such as APMS, OES, Langmuir Probe, Actinometry, XPS, LIF and end point detection can be attached to the ICP Etching system to study the selectivity, etch gas chemistry, etch rate, plasma mechanism of the etching process and the relation among the parameters in simple, detail and in real time. Furthermore, improvement and modification can be made either on the system or process condition with the studies from in-situ diagnostic.

Usually, selective etching of silica with a metal mask is obtained in ICP RIE plasma that utilises fluorocarbon gases [1-4]. Theoretically, the formation of a fluorocarbon film by radical deposition on the chromium mask surface reduces the chromium mask etch rate. In high density plasma sources, the higher degree of

dissociation and the high ionic density would strongly affect the selectivity of the etching process [5]. Addition of new chemistries can be study to improve selectivity without decreasing the silica etch rate too much and in parallel with the studying of the etching mechanism and plasma chemistry in order to anticipate the etching process [6-11].

In-situ diagnostics such as mass spectrometry, optical emission spectroscopy (OES) and Langmuir probes are very important for the understanding of etch process [12] and also fundamental for the validation of plasma modelling. Mass spectrometry and OES can be performed for a large range of gas mixtures and residence time. Otherwise, absolute radical concentrations can be calculated by using APMS and the following analysis of the plasma by mass spectrometry, Langmuir probe and optical emission spectroscopy. Moreover, the analysis feature can be expanded to the advancement of etch gases mixture and variety composition of waveguide channel studies in the future.

Absolute radical concentrations of etch gas can be determined by APMS and the atomic fluorine concentration can be sampled by Optical Emission Spectroscopy (OES) by using argon actinometry. OES was also used to characterize the plasma phase $\cong 10$ mm above the wafer surface. Subsequently, appearance potential mass spectrometry (APMS) is used to detect the dominant species such as CF_3 , CF_2 , CF and etc. By knowing the ionization cross sections [13–17], the extraction efficiency from the plasma chamber to the mass quadrupole [18], it is possible from the appearance mass spectrometry curves to calculate the absolute concentrations of the radicals produced in the plasma.

Langmuir probe measurements which can be associated with a plot of the bias power versus bias voltage to determine the ion flux and the essential parameter for silica

etching. The ion flux is an essential parameter for the etching of silicon oxide [19]. This parameter is usually determined by means of Langmuir probe in inert gases specifically argon and more generally in non-polymerizing atmospheres. The Langmuir probe is positioned in the plasma through one of the side flanges of the chamber, allowing determination of the electrical characteristics of the discharge: electron density and temperature, ion density, plasma and floating potentials and Electron Energy Probability Function (EEPF).

However, information about the energy delivered by neutral particles is usually hard to access experimentally. Calculating the energy of particles arriving at the substrate position from MC simulation results makes it possible to extract information about the average energy of deposited particles and to study the dependence of the average energy of neutrals on changing gas pressure at the substrate surface. Otherwise, plasma parameters such as gas discharge; residence time and follow the consecutive variation of plasma species (ion, radicals and etc.) can be studied extendedly to determine the mixture of etch gases and process condition prior to optimize the silica core etching process.

By the way, argon actinometry which is used to obtain information on the atomic fluorine concentration within the plasma reactor from measured F (7037 Å) and Ar (7504 Å) optical line intensities. Argon actinometry is also used to detect variation of the electron density and/or the electron temperature. Actinometry on fluorine atoms often used for the atomic fluorine relative concentration in low pressure plasmas. In the absence of dissociative excitation and quenching, the fluorine line intensity (7037 Å) is proportional to the electron density to the excitation coefficient by electronic collision which depends on the electron temperature (more precisely on the electron energy

distribution function (EEDF). Somehow, quenching of excited states may invalidate actinometry measurement.

In the dry etching process, X-ray Photoelectron Spectroscopy (XPS) can be used for chemistry study. XPS is a quantitative spectroscopic technique that measures the empirical formula, chemical state and electronic state of the elements that exist within a material. XPS spectra are obtained by irradiating a material with a beam of X-rays while simultaneously measuring the kinetic energy and number of electrons that escape from the top 1 to 10 nm of the material being analyzed.

XPS is a surface chemical analysis technique that enables chemistry analysis of the surface of a material. This occurs in its "as received" state, or after some treatment such as: fracturing, cutting or scraping in air or UHV to expose the bulk chemistry. Other treatments are ion beam etching to clean off some of the surface contamination, exposure to heat to study the changes due to heating, exposure to reactive gases or solutions, exposure to ion beam implant, and exposure to UV light, for example. In addition, XPS feature for uniformity mapping and depth profiling. XPS is also known as ESCA an abbreviation for Electron Spectroscopy for Chemical Analysis. XPS detects all elements with an atomic number (Z) between those of lithium ($Z=3$) and lawrencium ($Z=103$). This limitation means that it cannot detect hydrogen ($Z=1$) or helium ($Z=2$). Detection limits for most of the elements are in the parts-per-thousand (PPT_h) range. XPS is routinely used to analyze inorganic compounds, metal alloys, semiconductors, polymers, pure elements, catalysts, glasses, ceramics, ion modified materials and many others. Somehow, chemical modification of the surface after plasma exposure can be investigated by using quasi-in situ XPS.

Alternatively, in-situ diagnostic methods to understand the processes at the surface by probing the surface layer that forms during steady-state etching, using laser induced thermal desorption (LITD) with detection of the desorbed species by laser-induced fluorescence (LIF). This technique has been termed laser desorption-laser-induced fluorescence (LD-LIF) analysis. Laser desorption laser-induced fluorescence (LD-LIF) analysis to determine the surface coverage of fluorocarbon during steady-state etching. Laser interferometry was used to measure etch rates and on the other hand optical emission spectroscopy, actinometry and Langmuir probe analysis were used to characterize the plasma [20].

Laser-induced fluorescence (LIF) is a spectroscopic method used for studying structure of molecules, detection of selective species and flow visualization and measurements. The species to be examined is excited with help of a laser. The wavelength is often selected to be the one at which the species has its largest cross section. The excited species will after some time, usually in the order of few nanoseconds to microseconds, de-excite and emit light at a wavelength larger than the excitation wavelength. This light, fluorescence, is measured.

Two different kinds of spectra exist, LIF-spectra and excitation scans. The LIF-spectra are performed with a fixed lasing wavelength, as above and the fluorescence spectrum is analyzed. Excitation scans on the other hand collect fluorescent light at a fixed emission wavelength or range of wavelengths. Instead the lasing wavelength is changed. An advantage over absorption spectroscopy is that it is possible to get two- and three-dimensional images since fluorescence takes place in all directions (i.e. the fluorescence signal is isotropic). The signal-to-noise ratio of the fluorescence signal is

very high, providing a good sensitivity to the process. It is also possible to distinguish between more species, since the lasing wavelength can be tuned to a particular excitation of a given species which is not shared by other species.

LIF is useful in the study of the electronic structure of molecules and their interactions. It has also been successfully applied for quantitative measurement of concentrations in fields like combustion, plasma, spray and flow phenomena (such as Molecular tagging velocimetry), in some cases visualizing concentrations down to nanomolar levels.

In order to monitoring etching process and etch result, End Point Detection (EPD) system is suggested to precisely control etch depth; etch duration and termination time whereas dry etching has less etch selectivity than wet etching by using LI to determine the end point. Otherwise, real time detection enable analysis of etch selectivity, etch rate and process condition hassle less.

The two methods for End Point Detection (EPD): Laser Interferometry (LI) and Optical Emission Spectroscopy (OES) are both are applicable to Failure Analysis (FA) etching. LI endpoint detection works with the principle that reflection of a laser beam from two interfaces will cause constructive or destructive interference at the point where they are combined. If the distance between the two interfaces varies then the interference pattern also varies.

Typically the surfaces used during etching are the top of the etching surface and an underlying layer. Using the variation in distance as the surface is etched allows calculation of the whereabouts within the material the etch depth has reached. LI end-point detection can be used on layer removal steps. Multi-step recipes using laser end-

point can be written to provide a fully automated failure analysis capability. Using this trace it is possible to accurately assess the etch depth has reached and offering immediate control of the etching process. Moreover, the laser interferometry method is able to analysis any size of wafer piece or chip.

OES works on the principle that excited particles within plasma will emit light at very specific frequencies depending on their atomic composition. Monitoring the emission intensity of the wavelengths, which it correspond to certain species, allows to track the amount of the material in the plasma, and hence whether a particular material has been completely removed from the etch surface. The OES system has the benefit that it does not require alignment for every run, it simply looks at optical emission from the whole plasma. This means the endpoint is more accurate for the whole (average) of the wafer rather than a single point on the wafer.

Contemporary etching selectivity and its reproducibility are key issues in the etching of silica (SiO_2) in Ultra Large Scale Integration (ULSI) processing. In various plasma sources, especially in high density sources such as ICP, ECR, etc., the controlling method of F atom density relative to CF_x radical density has become an essential problem. Surface conditions of the substrate and chamber walls, however, are reflected in the gas phase reactions inevitably, so that in situ diagnostics of both gas phase species and surface bonding states are required for understanding the overall chemistry in silica (SiO_2) etching [21].

For instance, two new techniques for the gas phase diagnostics such as Vacuum Ultraviolet Laser Absorption Spectroscopy (VUV-LAS) [22] using a tunable laser around 95.5nm region for the detection of F atoms and Electron Attachment Mass Spectrometry

(EAMS) [23] for the detection of polymerized species. VUV-LAS has an advantage in the determination of absolute density with higher accuracy, and EAMS is suited for detecting big cluster molecules or radicals with less fragmentation. For the in situ surface diagnostics Fourier-transform Infrared Phase-Modulated Spectroscopic Ellipsometry (FT-IR PMSE) [24] can be use to diagnose surface bonds on silica thin film formed by exposing to plasmas. Chemical bonds such as $-\text{CF}_x$, $-\text{CH}_x\text{F}_y$, $-\text{SiF}_x$ as well as Si-C and C-C have been detected successfully by this method.

Systematic measurements of radical densities can carried out in various source gases such as CF_4 , C_2F_6 and C_4F_8 , and the effects of dilution gases such as Ar, H_2 and O_2 for further investigation. For understanding the production and loss processes of those radicals, the rise and fall characteristics of the densities can be measure by the method of pulse discharge. At the same time the changes in the surface chemical bonds can be monitor with FT-IR PMSE and their dependence on the discharge conditions and substrate bias conditions can be investigate.

Furthermore, measurements of C_xF_y radicals in the gas phase with set-up laser induced fluorescence (LIF) in ICP Etching system. Additional, XPS analyses of substrate combine together with the data obtained by laser induced fluorescence, and the reaction chemistry in the etching of SiO_2 will be study for better selectivity and reproducibility.

In the mean time, the in-situ diagnostic equipments also can be applied to understanding the process condition of DC Magnetron Sputter System. Moreover, this leads to studies the chromium deposition process in the similar techniques and improves the process condition such as deposition rate, thickness, density and uniformity.

5.2.2 ICP Etch System

In order to optimize the ICP RIE system, both RF power generators including ICP and Bias Powers are suggested to be upgraded to 3kW and to 1kW, respectively. The upgrade of Bias Power is optional as it is not very critical in the process duration during research and development stage. Isolation of the reflected power of RF may also be considered to ensure the plasma stability of ICP RIE system is in parallel with the upgrade of RF power.

Alternatively the reactor chamber can be equipped with temperature controller to reduce polymerization and contamination in the chamber. Process temperature of the chamber can be studied as one of the parameter to achieve further optimization of silica etching. Modification of ICP RIE system with compatible chlorine based chemistry for chromium dry etching can also be done as a low cost option to replace the single unit of RIE system.

In PR dry etching or developing and PR pattern removing, ICP RIE System will also be considered by modifying the fabrication process from wet to dry processing to improve the quality of PLC end products in the future work.

5.2.3 RIE System

The RIE System for chromium mask etching replaces the wet etching process to enable anisotropic etch interaction of chromium mask. This will improve the pattern to be transferred and increasing the efficiency and quality of the chromium mask. The

chromium mask dry etching process provides well control of the process condition and this will increase the yield of end products.

All etching applications require the transfer of PLC features from chromium metal mask pattern to the substrate with minimal critical dimension (CD) loss, or bias. This feature is an important component of device performance since at certain levels (e.g., at the gate electrode level), CD variations can contribute greatly to the operating frequency and loss. Etch selectivity to different films is also essential, since resist material is occasionally inadequate to provide a sufficient mask for features which must be etched. Thus, dry etching of chromium metal mask that utilises RIE system will be considered to optimize the planar profile for metal masking and photolithography development.

5.2.4 DC Sputter

The gas composition in the chamber can be monitored by a mass spectrometer (MS) to determine the influence on the film growth. On the other hand, plasma monitoring can be performed by an optical emission spectroscopy (OES) setup. Analysis of the emitted spectral lines allows conclusions on the sputter process.

The energy of bombarding ions can easily be tuned by applying substrate bias. The flux density can be estimated from electrostatic plasma probe measurements that incorporates saturation current at high negative bias voltages. However, information about the energy delivered by neutral particles is usually hard to access experimentally. Calculating the energy of particles arriving at the substrate position from Monte Carlo

(MC) simulation results makes it possible to extract information about the average energy of deposited particles. This also allows to study the dependence of the average energy of neutrals on the changing gas pressure at the substrate surface.

In order to improve the uniformity of chromium deposition, larger chromium target is suggested. Practically, the directional randomness of the sputtering process is provided when the target size is larger than the wafer. This results in good step coverage in which the uniformity of the thin film is over a geometrical step although some thinning can occur near corners. The deposited film has a very fine granular structure and it is usually under stress [25]. The stress levels vary with the sputter power and the chamber pressure during deposition where tensile stress occurs at lower power and higher pressure and compressive stress occurs at higher power and lower pressure. The transition between compressive and tensile regimes is often sharp (over a few tenths of a Pa), thus making the crossover an ideal point for zero-stress deposition that is difficult to control. In addition, heating the substrate during deposition is sometimes used to reduce the film stress.

References

- [1] Heinecke R A 1975 Solid State Electron. **18** 1146
- [2] Ephrath L M 1979 J. Electrochem. Soc. **126** 1419
- [3] Ephrath L M and Petrillo E J 1982 J. Electrochem. Soc. **129** 2282
- [4] Lehmann H W and Widmer R 1978 J. Vac. Sci. Technol. **15** 319
- [5] F Gaboriau, G Cartry, M-C Peignon and Ch Cardinaud, "Etching mechanisms of Si and SiO₂ in fluorocarbon ICP plasmas: analysis of the plasma by mass spectrometry, Langmuir probe and optical emission spectroscopy", J. Phys. D: Appl. Phys. **39** (2006) 1830–1845
- [6] Bell F H, Joubert O, Oehrlein G S, Zhang Y and Vender d 1994 J. Vac. Sci. Technol. A **12** 3095
- [7] Fukasawa T, Nakamura A, Shindo H and Horiike Y 1994 Japan. J. Appl. Phys. **33** 2139
- [8] Doh H H, Kim J H, Lee S H and Whang K W 1996 J. Vac. Sci. Technol. A **14** 2827
- [9] Den S, Kuno T, Ito M, Hori M, Goto T, O'Keeffe P, Hayashi Y and Sakamoto Y 1997 J. Vac. Sci. Technol. A **15** 2880
- [10] Rolland L 2000 PhD Thesis Nantes University (in French)
- [11] Doh H H, Kim J H, Lee S H and Whang K W 1996 J. Vac. Sci. Technol. A **14** 1088
- [12] Gaboriau F, Fernandez-Peignon M-C, Cartry G and Cardinaud Ch 2005 J. Vac. Sci. Technol. A **23** 226
- [13] Christophourou L G and Olthoff J K 1998 J. Phys. Chem. Ref. Data **27** 1–29
Christophourou L G and Olthoff J K 1999 J. Phys. Chem. Ref. Data **28** 967
- [14] Tarnovsky V, Levin A, Deutsch H and Becker K 1996 J. Phys. B **29** 139
- [15] Baiocchi F A, Wetzel R C and Freund R S 1984 Phys. Rev. Lett. **53** 771
- [16] Wang D P, Lee L C and Srivastava S K 1988 Chem. Phys. Lett. **152** 513
- [17] Janev R K (JA AI CH), Wang J G, Murakami I and Kato T 2001 Natl Inst. Fusion sci. (Data Rept.), Nagoya, JA (report) 68
- [18] Chevolleau T 1998 PhD Thesis Nantes University (in French)
- [19] Rueger N R, Beulens J J, Shaepkens M, Doemling M F, Mirza J M, Standaert T E F M and Oehrlein G S 1997 J. Vac. Sci. Technol. A **15** 1881
- [20] Jae Y. Choe, Irving P. Herman, Vincent M. Donnelly, "Analysis of the etching of silicon in an inductively coupled chlorine plasma using laser thermal desorption," J. Vac. Sci. Technol. A **15.6.**, Nov/Dec 1997
- [21] Kunihide Tachibana, "Gas Phase and Surface Reactions in SiO₂ Etching", Department of Electronic Science and Engineering, Kyoto University Yoshida-Honmachi, Sakyo, Kyoto 606-8501, Japan
- [22] K. Tachibana and H. Kamisugi: to be submitted.
- [23] W.W. Stoffels, E. Stoffels and K. Tachibana: J. Vac. Sci. Technol. A, **16**, 87 (1998).

- [24] G.M.W. Kroesen, H-J. Lee, H. Moriguchi, H. Motomura, T. Shirafuji and K. Tachibana: J. Vac. Sci. Technol. A, 16, 225 (1998).
- [25] Thornton, J. A., and D. W. Hoffman, "Stress Related Effects in Thin Films," Thin Solid Films, Vol. 171, 1989, pp. 5–31.

LIST OF PUBLICATION

Conferences

[1] Khoonseah Chuah, Sulaiman Wadi Harun and Harith Ahmad, “Inductively Coupled Plasma of Fluorocarbon Plasma Glass Etching Process on Planar Lightwave Circuit Device Fabrication” International Conference on Transparent Optical Networks Mediterranean Winter 2007 (ICTON-MW 2007), 6-8 Dec 2007, Sousse, Tunisia.

[2] Khoonseah Chuah, Sulaiman Wadi Harun and Harith Ahmad, “Comparison of Tetrafluoromethane and Hexafluoroethane in Inductively Coupled Plasma Glass Etching Process” 3rd Mathematics and Physical Sciences International Graduate Congress (3rd MPSGC), 14-16 Dec 2007, University of Malaya, Malaysia.

APPENDIXES

Appendix 1: Wet Etching

Table 1: Liquid, Plasma, and Gas Phase Etchants of Silicon [1, 2]

	HF:HNO ₃ :CH ₃ COOH	KOH	EDP	N(CH ₃) ₄ OH (TMAH)	SF ₆	SF ₆ /C ₄ F ₈ (DRIE)	XeF ₂
Etch type	Wet	Wet	Wet	Wet	Plasma	Plasma	Vapour
Typical formulation	250ml HF, 500ml HNO ₃ , 800ml CH ₃ COOH	40 to 50 wt%	750ml Ethylenediamine, 120g Pyrochatechol, 100ml water	20 to 25 wt%			Room temperature, vapour pressure
Anisotropic	No	Yes	Yes	Yes	Varies	Yes	No
Temperature	25°C	70-90°C	115°C	90°C	0-100°C	20-80°C	20°C
Etch rate (μm/min)	1 to 20	0.5 to 3	0.75	0.5 to 1.5	0.1 to 0.5	1 to 15	0.1 to 10
{111}/{100} selectivity	None	100:1	35:1	50:1	None	None	None
Nitride etch (nm/min)	Low	1	0.1	0.1	200	200	12
SiO ₂ etch (nm/min)	10-30	10	0.2	0.1	10	10	0
p ⁺⁺ etch stop	No	Yes	Yes	Yes	No	No	NO

Appendix 2: Fundamental of Plasma

Plasma is typically an ionized gas in physics and chemistry. Plasma is considered to be a distinct state of matter, apart from gases. Plasmas consist of freely moving charged particles which containing some or all of the components such as electron, positive ions, atoms and

molecules. The plasma is generated and maintained via collisions producing a certain distribution of ionic and neutral species.

Plasmas are common in nature and formed at high temperatures when electrons are stripped from neutral atoms. For instance, stars are predominantly plasma. Taking into consideration the energy of particles constituting it, plasma is often referred to as the fourth state of matter because of their unique physical properties, distinct from solids, liquids and gases. After all, plasma is created by adding energy to a gas. The densities and energies of neutral and charged particles are the fundamental parameters that characterize the plasma.

Excitation of plasma requires partial ionisation of neutral atoms and/or molecules of a medium. There are several ways to cause ionisation: collisions of energetic particles, strong electric fields acting on bond electrons, or ionising radiation. The kinetic energy for ionising collisions may come from the heat of chemical or nuclear reactions of the medium, as in flames, for instance. Alternatively, already released charged particles may be accelerated by electric fields, generated electromagnetically or by radiation fields. If at least as many charge carriers are created per time unit as recombine, the plasma can be sustained.

Plasma excitation by electromagnetic fields can be classified according to frequency, energy and pressure. In frequency classification of plasmas, electrical discharges are applied in a plasma source for the plasmas generation. A frequency mode plasma fall into direct current (DC) discharge, pulsed DC discharge (kHz), radio-frequency discharge (MHz), microwave discharge (GHz) and laser plasma (PHz).

The quality of the coupling of an exciting field of given frequency to a charged particle depends on the position and shape of the plasma resonance. It critically determines the character of the electrical discharge. If the more massive ions cannot follow the oscillating electromagnetic

field, the exciting frequency is called high frequency. In this case, the main fraction of the power is transferred to the electrons.

On the other hand, energy coupling mode of plasma excitation categorized into inductively coupled plasma, capacitively coupled plasma, wave-heated plasma and electrode-less plasma excitation. Three types of inductively coupled plasma which are solenoid coil, planar coil and helical resonator. Wave-heated plasma consists of four type plasma generation modes which are electron cyclotron resonance, helicon discharge, surface-wave-sustained mode and resonator mode. The Electron Cyclotron Resonance (ECR) ion source makes use of the Electron Cyclotron Resonance to heat the plasma. Microwaves are injected into a volume, at the frequency corresponding to the Electron Cyclotron Resonance defined by a magnetic field applied to a region inside the volume whereas the volume contains a low pressure gas. A helicon discharge is an excitation of plasma by helicon waves induced through radio frequency heating which using of a magnetic field directed along the axis of the antenna. The surface-wave-sustained mode generates plasma by propagation of electromagnetic surface waves which allows generating uniform high-frequency-excited plasmas in volumes whose lateral dimensions extends over several wavelengths of the electromagnetic wave. In resonator mode, plasmas excited are less resistant against detuning and plasma density does not exceed the critical density.

Other than energy coupling mode, there is pressure mode which is the third classification of plasma excitation method. Pressure mode plasma excitation consists of low pressure discharge and atmospheric pressure discharge.

Appendix 3: Plasma Processing

Plasma activation is another name for plasma functionalization. It is done with the intent to alter or improve properties of the surface prior to coating, painting, etc. In most cases, the surface in question is surface of a polymer material and weakly ionised oxygen plasma is used.

Surface activation is a result of the processes such as removal of weak boundary layers, cross-linking of surface molecules and generation of polar groups. Removal of weak boundary layers process involved in plasma removes of surface layer with the lowest molecular weight, at the same time it oxidises the uppermost atomic layer of the polymer. On the other hand, cross-linking of surface molecules process take part in oxygen radicals and UV radiation if present help break up bonds and promote the three dimensional cross bonding of molecules. Other wise, generation of polar groups process refer to oxidation of the polymer is possible for the increase in the polar groups which is directly related to the adhesion properties of the polymer surface.

Plasma modification which is involved in material properties changes either in physical or chemical. Other wise, plasma modification may happen in both physical and chemical properties change. In some cases, plasma modification used to change the tendency of material property to react to appropriate chemical agent as to improve the surface processing quality and yield.

Plasma polymerization technique uses plasma sources to generate a gas discharge that provides energy to activate or fragment gaseous or liquid monomer, often containing a vinyl group, in order to initiate polymerization. Plasma polymerization can be used to deposit polymer thin films. By selecting the polymer thin films. By selecting the monomer type and the energy density per monomer, known as Yasuda parameter, the chemical composition and structure of the resulting thin film can be varied in a wide range.

Appendix 4: Heterogeneous Process

In plasma processing, the term heterogeneous processes includes all chemical and physical reactions that occur when fluxes of species are incident on a surface and the interaction of the incident species with the species residing on the surface results in either the gasification of the material or the formation of a new material. Surface processes are of central importance in plasma processing and the entire purpose of the technology is to modify a surface, to etch or deposit material, or perhaps to clean or treat the surface in some way. Low-pressure plasma turns out to be an extraordinarily powerful medium within which to effect surface chemical and physical modifications with little impact on bulk material, at low cost, and over large areas. However, plasma-surface interactions are among the most complex and least well understood aspects of plasma processing technology. Several techniques, experimental and computational, are suggested as most promising in order to advance the state of the database and to improve treatments of plasma-surface interactions in tool scale and feature scale models.

Heterogeneous processes that are of interest to plasma processing include the following adsorption of radicals at specific surfaces; reactions to form certain intermediate or stable products; desorption (etching) or incorporation into a growing film (deposition) of the products formed; ion enhancement or suppression; sputtering; particle and energy reflection; ion implantation and production of defects; diffusion effects (on the surface, through the reaction layer, and ion-enhanced diffusion effects); redeposition of desorbed products on the sidewalls of structures, the walls of the reactor, and elsewhere; the mutual interaction of etching and deposition processes that occur in parallel, e.g. in fluorocarbon-based silicon dioxide etching; surface roughening; electron-reduced desorption; and electron emission.

However in the recent study, heterogeneous process combines both advantageous of physical and chemical reaction in plasma processing enable advance material processing technology and further development in semiconductor, photonics and nanotechnology.

The data necessary to characterize or simulate these processes should be available as a function of the relevant parameters, e.g., temperature, crystallinity and coverage of the substrate, kinetic or internal energy, and angle of incidence of the incident species. In many cases, the functional form relating these relevant parameters and the processes stated above are not known. Synergistic effects between ions and neutrals that strike the surface simultaneously are often essential and also need to be characterized.

Appendix 5: Technology of Dry Etching

Modern very large scale integration (VLSI) processes avoid wet etching, and use plasma etching instead. Plasma systems can operate in several modes by adjusting the parameters of the plasma. Ordinary plasma etching operates between 0.1 and 5 Torr. (This unit of pressure, commonly used in vacuum engineering, equals approximately 133.3 pascals.) The plasma produces energetic free radicals, neutrally charged, that react at the surface of the wafer. Since neutral particles attack the wafer from all angles, this process is isotropic.

The source gas for the plasma usually contains small molecules rich in chlorine or fluorine. For instance, carbon tetrachloride (CCl_4) etches silicon and aluminium, and trifluoromethane etches silicon dioxide and silicon nitride. A plasma containing oxygen is used to oxidize ("ash") photoresist and facilitate its removal. Other wise, fluorine based etch gases such as SF_6 and CF_4 used for silicon dioxide etches.

In dry etching technology, gas discharges are used to generate plasma. Excitation of plasma requires partial ionization of neutral atoms or molecules in a medium, through collisions between particles, electric fields or ionizing radiation. The kinetic energy for ionizing may come from chemical reaction in the medium or it may come from the electric and magnetic fields. Charged particles may be accelerated by electromagnetic fields, which are a tool to generate plasma.

Plasma excitation due to electromagnetic fields can be classified according to frequency, energy and pressure. The frequency of the exciting field consists of direct current (DC) discharge, pulsed DC discharge (kHz), radio-frequency discharge (MHz), microwave discharge (GHz) and laser plasma (PHz). The plasma excitation of energy coupling mode including Capacitively Coupled Plasma (CCP), Inductively Coupled Plasma (ICP), Wave Heated Plasma and Electrodeless Plasma Excitation. Lastly, the pressure range of plasma excitation falls into Low Pressure Discharge and Atmospheric Pressure Discharge.

In mega hertz (MHz) range, there are broadly in electronics and physics application whereas Joule heating or ohmic heating refers to the increase in temperature of a conductor as a result of resistance to an electrical current flowing through it. At an atomic level, Joule heating is the result of moving electrons colliding with atoms in a conductor, where upon momentum is transferred to the atom, increasing its kinetic energy. When similar collisions cause a permanent structural change, rather than an elastic response, the result is known as electromigration. On the other hand, microwave being high frequency electromagnetic radiation in the giga hertz (GHz) range are capable of exciting electrode-less gas discharge. Microwave excited plasmas have two appealing properties. Firstly, they are well suited to generate large area plasmas of high plasma density if applied in surface wave sustained mode. In addition, both in surface wave and

resonator mode, they can exhibit a high degree of spatial localization. This allows to spatially separating the location of plasma generation from the location of surface processing.

In the energy coupling mode of plasma excitation, Capacitively Coupled Plasma (CCP) is one of the most common types of industrial plasma sources. It essentially consists of two electrodes separated by a small distance, placed in a reactor. The gas pressure in the reactor can be lower than atmosphere or it can be atmospheric. A typical CCP system is driven by a single radio-frequency (RF) power supply, typically at 13.56 MHz. One of the two electrodes is connected to the power supply and the other one is grounded. As this configuration is similar in principle of a capacitor in an electric circuit, the plasma formed in this kind of dry technology is called capacitively coupled plasma.

Inductively Coupled Plasma (ICP) is a plasma source in which the energy is produced by electrical currents from induction of electromagnetic whereas time-varying magnetic field applied at the electrode. Unlike capacitively coupled plasma discharges, inductively coupled plasma discharges are of relatively high electron density, which means that high concentration of plasma can be reached. In high ion and electron density, the flux of particles is larger on the treated surface. Therefore, ICP discharges have important applications where a high density of plasma is necessary. Another advantage of ICP discharges is that the electrodes are completely outside the reactor chamber whereas CCP's electrodes are inside the reactor and are thus exposed to the plasma and possible erosion from reactive chemical species. Since erosion of electrodes severely limits operational lifetimes and introduces electrode atoms into the plasmas, and thus ICP discharge play an important role in recent dry etching technology.

In Electron Cyclotron Resonance (ECR), an electron in a static and uniform magnetic field will move in a circle due to the Lorentz force. The circular motion may be superimposed

with a uniform axial motion, resulting in a helix, or with a uniform motion perpendicular to the field and in the presence of an electrical or gravitational field, resulting in a cycloid. Ionized plasma may be efficiently produced or heated by superimposing a static magnetic field and a high-frequency electromagnetic field at the ECR frequency. In the toroidal magnetic fields, the magnetic field decreases with the major radius which results the location of the power can be controlled within about a centimetre.

Helicon discharge is the excitation of plasma by helicon waves induced through radio frequency heating. The difference between a helicon plasma source and ICP is the presence of a magnetic field directed along the axis of the antenna. The presence of the magnetic field creates a helicon mode of operation with higher ionization efficiency and greater electron density.

Surface wave sustained mode generate plasma which excited by propagation of electromagnetic surface waves. The surface wave sustained mode allows to generate uniform high-frequency excited plasma in volumes whose lateral dimensions extends over several wavelengths of the electromagnetic wave in vacuum such as microwaves of 2.45 GHz. But microwave plasma sources without magnetic field not been considered suitable for the generation of high density plasmas. Electromagnetic waves cannot propagate in over-dense plasmas. The wave is reflected at the plasma surface due to the skin effect and becomes an evanescent wave. Its penetration depth corresponds to the skin depth. The non-vanishing penetration depth of an evanescent wave opens an alternative way of heating plasma. Instead of traversing the plasma, the conductivity of the plasma enables the wave to propagate along the plasma surface. The wave energy is the transferred to the plasma by an evanescent wave which enters the plasma perpendiculars to its surface and decays exponentially with the skin depth. Surface wave sustained plasma can be operated in a large variety of recipient geometries. The pressure range

accessible for surface wave excited plasmas depends on the process gas and the diameter of the recipient.

In the resonator mode, the plasma density does not exceed the critical density. A standing electromagnetic wave, which is not confined by a resonator cavity, penetrates the plasma and sustains it in the regions of highest field intensity. Plasmas excited in resonator mode are less resistant against detuning.

Electrode-less plasma excitation methods include helicon plasma sources, ICP and surface wave sustained discharges. Electrode-less high frequency discharges have two important advantages over plasmas using electrodes which are no sputtering of the electrodes occurs and allows generating spatially extended plasmas with electron densities that exceed the critical density.

Other than energy coupling mode, there is pressure mode which is the third classification of plasma excitation method. Pressure mode plasma excitation categorized into low pressure discharge and atmospheric pressure discharge.

The dry etching technology can split in four separate classes called sputter etching, reactive ion etching (RIE), plasma etching and vapour phase etching. Sputter etching is essentially RIE without reactive ions. The systems used are very similar in principle to sputtering deposition systems. The big difference is that substrate is now subjected to the ion bombardment instead of the material target used in sputter deposition.

Sputter etching or ion milling uses lower pressures, often as low as 10^{-4} Torr (10 mPa). It bombards the wafer with energetic ions of noble gases, often Ar^+ , which knock atoms from the substrate by transferring momentum. Because the etching is performed by ions, which approach

the wafer approximately from one direction, this process is highly anisotropic. On the other hand, it tends to display poor selectivity.

In RIE, the substrate is placed inside a reactor in which several gases are introduced. RIE operates under conditions intermediate between sputter and plasma etching within 10^{-3} and 10^{-1} Torr. Deep reactive-ion etching (DRIE) modifies the RIE technique to produce deep, narrow features. The plasma is struck in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards, and react at, the surface of the material being etched, forming another gaseous material. This is known as the chemical part of reactive ion etching. There is also a physical part which is similar in nature to the sputtering deposition process. If the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction. It is a very complex task to develop dry etches processes that balance chemical and physical etching, since there are many parameters to adjust. By changing the balance it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic the combination can form sidewalls that have shapes from rounded to vertical.

A special subclass of RIE which continues to grow rapidly in popularity is deep RIE (DRIE). In this process, etch depths of hundreds of microns can be achieved with almost vertical sidewalls. The primary technology is based on the so-called "Bosch process", named after the German company Robert Bosch which filed the original patent, where two different gas compositions are alternated in the reactor. The first gas composition creates a polymer on the surface of the substrate, and the second gas composition etches the substrate. The polymer is immediately sputtered away by the physical part of the etching, but only on the horizontal surfaces and not the sidewalls. Since the polymer only dissolves very slowly in the chemical part

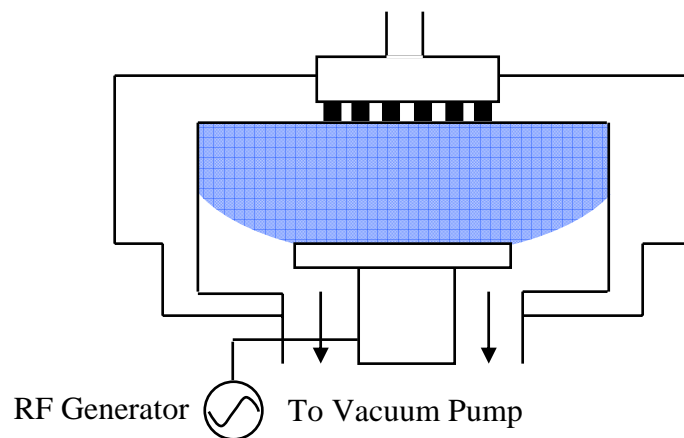
of the etching, it builds up on the sidewalls and protects them from etching. As a result, etching aspect ratios of 50 to 1 can be achieved. The process can easily be used to etch completely through a silicon substrate, and etch rates are 3-4 times higher than wet etching.

On the other hand, plasma etching is a dry etching method that assisted by plasma chemical reaction. Plasmas etching also known as plasma chemical etching where plasma created by RF power and etch gas introduced into chamber continuously without acceleration of ions by substrate bias power. Plasma chemical etching involved in pure chemical reaction without physical ion bombardment that offered high selectivity and isotropic etches. In plasma chemical etching, neutral and ionized species interact with the material's surface to form volatile products that prevent surface recoat by the reaction product.

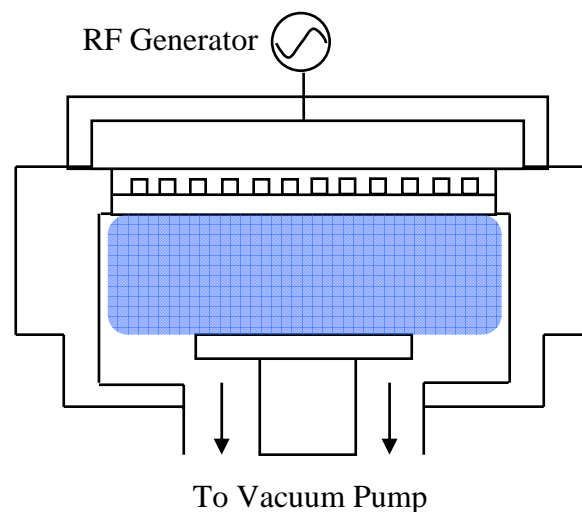
Vapour phase etching is another dry etching method, which can be done with simpler equipment than what RIE requires. In this process the wafer to be etched is placed inside a chamber, in which one or more gases are introduced. The material to be etched is dissolved at the surface in a chemical reaction with the gas molecules. The two most common vapour phase etching technologies are silicon dioxide etching using hydrogen fluoride (HF) and silicon etching using xenon difluoride (XeF_2), both of which are isotropic in nature. Usually, care must be taken in the design of a vapour phase process to not have bi-products form in the chemical reaction that condense on the surface and interfere with the etching process.

Generally, radicals and ions function as chemical reaction and ion bombardment respectively in dry etching process. Reactive species diffused onto the sample surface and absorbed by the surface. At the mean time, chemical reaction occurs and forming volatile by-product. On the other hand, by-product is desorbed form the surface and exhausted from the chamber.

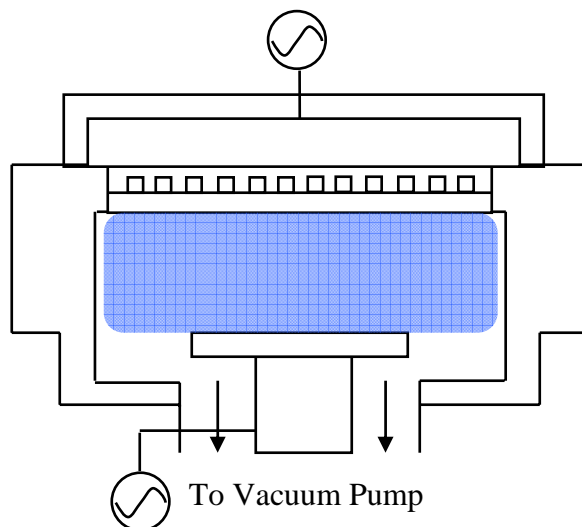
Dry etching systems are available in a variety of chamber configurations. Commonly, a choice of three technology streams as Reactive Ion Etching (RIE), Plasma Etching (PE) and Inductively Coupled Plasma Reactive Ion Etching (ICP RIE) is available, each having its own advantages. Three of the dry etch systems are shown in figure 3.2. During processing, process gases flow through the chamber, with flow rate controlled by mass flow controllers (MFCs) and chamber pressure controlled by an automatic throttle valve.



a) Reactive Ion Etching (RIE) System



b) Plasma Etching (PE) System



c) Inductively Coupled Plasma (ICP) or Inductively Coupled Plasma Reactive Ion Etching (ICP RIE) System

Figure 1: Schematic diagrams of (a) Reactive Ion Etching (RIE), (b) Plasma Etching (PE) and (c) Inductively Coupled Plasma Reactive Ion Etching (ICP RIE) dry etching system technology

In RIE mode, RF power is applied to the lower electrode to strike and maintain the plasma and to provide ion bombardment of the wafer through the generation of a DC bias on the lower electrode. This allows highly anisotropic etching of the Inter Metal Dielectric (ILD) layers, avoiding undercutting metal tracks and maintaining the integrity of the circuit formed by these tracks. Using PE mode, the power is supplied to the upper electrode while the lower is grounded. The plasma then etches materials isotropically producing a smooth, uniform finish. This mode is typically used when removing the upper cladding or passivation layers from device wafers.

In ICP RIE mode, RF power is applied to both ICP source and substrate electrode to generate the etch plasma. Ion energy at the substrate is monitored by measurement of the DC bias generated on the lower electrode, and is controlled mainly by the RF power supplied to this electrode. With the increased ion density from the ICP source the heat load on the samples is also increased. In order to maintain profiles the wafer temperature has to be actively controlled so

they are mechanically or electrostatically clamped to a temperature-controlled electrode and helium pressure is applied to the back of the wafers to provide good thermal contact between chuck and wafer.

Appendix 6: ICP Dry Etching Process

Challenges in dry etching evolving to such dimensions have come from the implementation of antireflective coatings and thinner, more etch-sensitive photoresists; the increased aspect ratios needed to meet design requirements; the additional hard-mask etching steps needed at levels at which lithography is unsuitable for patterning; and increased selectivity requirements, such as the requirement that contact structures be self-aligning. The circuit density and performance requirements become dictate tighter specifications for line width variations permitted across a wafer, micro-loading effects, and device damage. As a result, plasma-etching systems for critical levels are migrating from traditional multi-film, capacitively coupled low-density-plasma systems to medium- and high-density-plasma systems employing exotic or highly polymerizing chemical species specifically designed for one type of film which known as Inductively Coupled Plasma (ICP) etch system or Inductively Coupled Plasma Reactive Ion Etch (ICP RIE) system.

Interactions with resist/film residue, topography, cleaning technology, and dopant profiles all play key roles in determining appropriate dry etching processes. As complexity has increased, these interactions have become more important and more subtle. Meanwhile, the use of more complex chemical systems has evolved as the need for selective, high-aspect-ratio anisotropic features has developed. Simple chlorine- and fluorine-based systems have evolved into multiple-specialty-gas selections independently controlling polymer deposition and etching.

In Planar Lightwave Circuit (PLC) fabrication process, the deposited silica core layer is gone through chromium coating, photolithography process with PR processing and chromium metal masking. However, the main important process is to etch and transfer chromium mask pattern to silica core layer by precise and well control Inductively Coupled Plasma (ICP) etch system. Since the etch materials are focus in PR residue and silica core layer with chromium mask, oxygen gas and fluorine based etch gas are chosen as mainly to engineered the core layer for low loss planar waveguide channel.

ICP etch system combined both of chemical and physical etch as to perform anisotropic etch and good surface profile for planar etching in small feature size and makes the critical dimension of waveguide channel possible for Planar Lightwave Circuit (PLC). ICP dry etching is used in Planar Lightwave Circuit (PLC) silica core etching process as to suit the need of vertical and smooth profile requirement. Maintenance of the system is important especially the reactor chamber cleaning is required periodically to ensure the optimum etch result. Advanced Etch Method such as controlled over-etches, estimated etch depth and uniform etches is important to study etching recipe and system limitation for appropriate etch condition.

Appendix 7: Description and Application of ICP Etch System

Inductively Coupled Plasma (ICP) etch system play an important role in material processing for Planar Lightwave Circuit (PLC) fabrication process. ICP etch system also known as Inductively Coupled Plasma Reactive Ion Etch (ICP RIE) system which use of plasma processing method that combined physical and chemical reaction in etching process. ICP is a type of plasma source where the energy is supplied by electrical currents which are produced by electromagnetic induction, that is, by time-varying magnetic fields. There are two types of ICP

geometries which are planar and cylindrical. In planar geometry, the electrode is a coil of flat metal wound like a spiral. In cylindrical geometry, it is like a helical spring. When a time-varying electric current is passed through the coil, it creates a time varying magnetic field around it, which in turn induces azimuthal electric currents in the rarefied gas, leading to break down and formation of plasma.

ICP etch system can be divided into four elements including the vacuum chamber, power supply, pressure control and gas supply. Vacuum chamber required Turbo Molecular Pump (TMP) and rotary pump for vacuum processing. Power supply consists of RF source power generator which including radio frequency power source, automatic matching network and matching network controller for plasma generating in etching process. Other wise, gauges and valves such as Baratron gauge, Pirani gauge, ion gauge, Automatic Pressure Controller (APC) and Throttle valve are required for pressure control feature. In addition, as supply piping lines for several gases are connected and feed into process chamber for plasma processing.

Dry Scrubber is subsystems of ICP etch system that designed to filter greenhouse gases such as nitrous oxide, sulphur hexafluoride, fluorocarbons, hydrocarbons, perfluorocarbons and chlorofluorocarbons type of gases that contribute to the global warming. Dry Scrubber consists of unique gas flow system and electrical control system that offers a safe, efficient and reliable solution for toxic and harmful gases treatment.

ICP etch system consist of vacuum system that utilized rotary pump and TMP as primary and secondary vacuum pump respectively, to enable high vacuum condition for the process requirement. TMP is connected in series with rotary pump as backing pump to enable TMP work efficiently. With rotary pump, the pressure can be pump down to as low as 10^{-3} Torr and parallel pumping with both rotary pump and TMP which can be attain pressure from 10^{-5} Torr to 10^{-11}

Torr. A backing pump for the TMP is capable of pumping oxygen which using perfluoropolyether (PFPE) type pump oil to prevent explosion issue.

Throttle valve is connected in conjunction of process chamber and TMP to control chamber pressure by APC as to attain preset chamber pressure for etching process. Throttle valve control the flow by opening, closing or partially obstructing various passageways to attain the pressure set by APC.

The types and quantity of gas used vary depending upon the etch process; for instance, sulphur hexafluoride (SF_6) and tetrafluoromethane (CF_4) are commonly used for etching silicon and silica respectively. Gas pressure is typically maintained in a range between a few millitorr and a few hundred millitorr by Throttle valve which set by APC.

In ICP etch system, plasma is generated by using Radio Frequency (RF) power generator which consists of radio frequency power supply, automatic matching network and matching network controller. The SEREN R1001 and R301 RF power source used as ICP Power and Bias Power respectively. Frequency of both the ICP and Bias RF power source provide 13.56 MHz, level-controlled radio frequency power output up to 1000 Watts (SEREN R1001) and 300 Watts (SEREN R301) respectively. The RF power source features of displaying forward and reflected RF Power, Control Mode, Power Supply Status and RF or DC Probe Voltage. The other features like forward power, Load Power Levelling and programmable pulsing also included. RF Power Supply consists of three levelling mode which are Forward Power Levelling mode, Voltage Levelling mode and Load Power Levelling mode.

Automatic Matching Network and MC-2 Matching Network Controller are used in conjunction with connected to Both ICP and Bias RF power source. AT-10 Automatic Matching Network and AT-3 Automatic Matching Network are used in ICP and Bias RF Power Generator

System respectively. Both AT-10 and AT-3 Automatic Matching Network are consists of two variable capacitors and single fixed inductor but feature for 1000 W and 300 W nominal input power respectively. The matching network circuit topology features an “L” type circuit which provides a wide tuning range and low insertion loss and delivering maximum power transfer to the plasma load from the configuration. Automatic Matching Networks are driven by variable capacitors which powered by servo-motors of SEREN MC-2 Matching Network Controller.

Etch gases such as Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) are using in the ICP etch system. Moreover, additive gases such as Oxygen (O_2), Hydrogen (H_2), Argon (Ar) and Nitrogen (N_2) processing gases are also included and connected to process chamber through standard steel piping line as feed appropriate gas or mixture gases into process chamber for material processing. The flow rate of gas is controlled by Mass Flow Controller (MFC) are used to controlled gas flow rate precisely whereas to ensure the consistency of gas or gases quantity to be feed into process chamber.

The demands of etching small features in integrated circuits have driven the development of high density plasma sources. One of the most successful methods of creating intense plasma is radio frequency induction. The plasma is sustained by an RF current (5-50 A) carried by an inductive element, usually an air-core coil. This current induces an electric field in the plasma region which is primarily tangential to the plasma boundary. The tangential component of the RF induction electric field may then penetrate the plasma region 1-2 cm and generate intensive plasma.

In this project, planar type ICP geometry is used for planar silica core etching. The geometry if the planar coupler is advantageous for processing planar wafer and it can be easily scaled to process larger wafer. In the planar geometry configuration, a planar inductive coil

placed on top of a dielectric window separates the plasma from the winding. ICP etch system is an evolution essence and modified from Capacitively Coupled Plasma (CCP) etch system. The benefit of ICP discharges is that they are relatively free of contamination because the electrodes are completely outside the reaction chamber. The electrodes of CCP etch system are placed inside the reactor and are thus exposed to the plasma and subsequent reactive chemical species. In addition, ICP etch system has improvement whereas surface damage due to high energy ion bombardment, commonly in capacitively coupled plasmas, is considerably reduced.

The high plasma density of ICP produces high ion and radical densities and thus high etch rate. ICP discharges are of relatively high ion and electron density whereas ICP discharges have wide applications in plasma chemistry and material processing. The ion energy toward the substrate is independently controlled by an RF bias applied to the wafer electrode.

ICP etch system is one of the plasma technology systems for various etching application especially in semiconductor and photonics fabrication. ICP etch system is also known as Inductively Coupled Plasma Reactive Ion etch (ICP RIE) system. ICP RIE of silica etching is a revolutionized and modified Bosch process which hybrid of passivation in parallel with etches process. ICP RIE system enable the combination of chemically reactive plasma and physical sputtering to remove material deposited on wafers which offered anisotropic and directional etches. Thus, ICP RIE etching is anisotropic, and it produces vertical sidewall that enables precise control and good reproducibility of the geometry and, accordingly, of the effective lateral index contrast of the waveguide structure. Commonly, anisotropic etching is etching it's induced by electrically controlling ions at appropriate energy.

Inductively coupled plasma is induced by a coil wrapped around a quartz chamber, as opposed to planar etching between two parallel electrodes. Low frequency or Radio Frequency

cycles through the coil at its designated frequency and induces plasma formation in the quartz chamber as it couples at opposite sides of the coil. The plasma may form whenever gas is exposed to an electric field. If the field is sufficiently strong, a high percentage of gas atoms will surrender an electron or two and become ionized. The resultant ionized gas and liberated energetic electrons comprise the gas plasma or plasma. The ionized gas atoms have relatively little kinetic energy unless they are accelerated through an electric field. When accelerated, they will bombard a surface with sufficient force to dislodge an atom from a target material. Plasma effects sputtering and etching processes by momentum transfer of material, and the use of reactive gases produces chemical modification as well.

The term sputtering refers to the process of dislodging atoms from a target material to coat a thin film onto a material of interest. The term etching refers to the use of plasma to remove atoms from a material of interest in order to clean the material or to modify the surface or thickness of the material. In both sputtering and etching, the plasma can be diffused or it can be directed for a more concentrated effect.

Plasma etching has several advantages over wet chemical processing. Surface tension phenomena of the liquid are eliminated, as is bubble formation, which may cause incomplete wetting. Plasma etching concludes rapidly upon termination of process, whereas liquid etching processes are difficult to end with precision. Disposal of toxic and corrosive liquids is obviated. The primary disadvantage of plasma processing is lower throughput. Plasma etching which uses gases present at ambient temperature without thermal phase change. These gases can be either inert or reactive. In the case of reactive gases, processing uses momentum transfer as well as the chemical properties of the reaction of the gas to the material of interest. In sputter process is

primarily physical, mostly diffused, and slightly directed. The ashing and etching process are diffused and relies more on chemical effects than on physical sputtering effects.

Appendix 8: Theory of ICP Etch System

ICP etch system is an important tool for semiconductor and photonics material processing, particularly to manufacture critical features. ICP discharges are of relatively high electron density, up to the order of $10^{11} - 10^{12} \text{ cm}^3$. As a result, ICP discharges have wide applications where high density plasma is necessary. Plasma is initiated in the system by applying a strong RF (radio frequency) electromagnetic field to the wafer platter. The field is typically set to a frequency of 13.56 megahertz, applied at a few hundred watts.

Inductively coupled plasma (ICP) is a type of plasma source in which the energy is supplied by electrical currents which are produced by electromagnetic induction, that is, by time-varying magnetic fields as shown in figure 2. The oscillating electric field ionizes the gas molecules by stripping them of electrons, creating plasma.

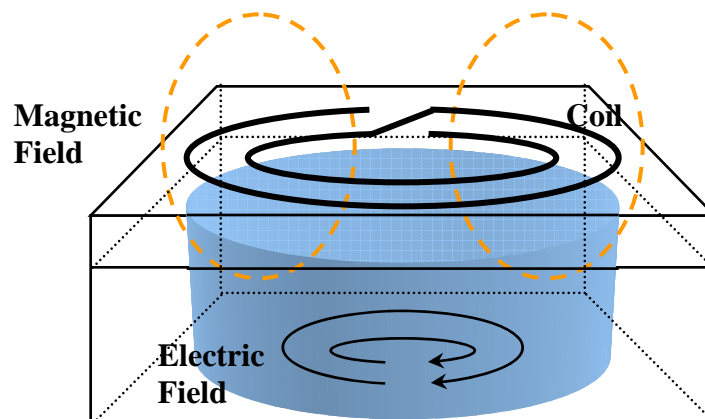


Figure 2: Plasma induced by time varying magnetic and electric field in ICP etching system

In each cycle of the field, the electrons are electrically accelerated up and down in the chamber, sometimes striking both the upper wall of the chamber and the wafer platter. At the same time, the much more massive ions move relatively little in response to the RF electric field. When electrons are absorbed into the chamber walls they are simply fed out to ground and do not alter the electronic state of the system. However, electrons absorbed into the wafer platter cause the platter to build up charge due to its direct current isolation. This charge build up develops a large negative voltage on the platter, typically around a few hundred volts. The plasma itself develops a slightly positive charge due to the higher concentration of positive ions compared to free electrons.

Because of the large voltage difference, positive ions tend to drift toward the wafer platter, where they collide with the samples to be etched. The ions react chemically with the materials on the surface of the samples, but can also knock off (sputter) some material by transferring some of their kinetic energy. Due to the mostly vertical delivery of reactive ions, reactive ion etching can produce very anisotropic etch profiles, which contrast with the typically isotropic profiles of wet chemical etching.

Etch conditions in an ICP etch system depend strongly on the many process parameters, such as pressure, gas flows, and RF power. However, anisotropic etching is directional and is induced by electrically controlling ions at some specific energy, or range of energies. A modified version of RIE is deep reactive-ion etching, used to excavate deep features.

Comparing of ICP etch system and CCP etch system, ICP has the advantage that relatively free of contamination whereas the design of electrodes are completely isolated from plasma by dielectric window. The time varying current circulates in the planar coil and induces time varying magnetic and electric fields and then generates and sustain the plasma. Some degree

of capacitive coupling of the antenna (coil) to the plasma is required to create secondary electrons via ion impact. Without secondary electron injection into plasma the latter becomes unstable. At the moment of plasma striking, the capacitive coupling is at its maximum level since there is no current to the plasma. ICP discharges are relatively high density at least one to two orders of magnitude larger than capacitively coupled plasmas.

ICP etch system is used for de-layering because it results in precise and repeatable etch rates, has good selectivity and produce anisotropic (directional) etching and prevent undercut. ICP etch systems are fast becoming the system of choice in front end production areas. They offer many advantages such as high etch rates, cleaner and high selective etches and much lower plasma damage due to the lower operating voltage at the sample surface. ICP system typically contains two RF power sources and each of these power sources introduces energy into the system in different ways. The ICP power is one of the RF power sources which introduce energy by the use of an RF induction coil upstream from the sample. This source does not couple its energy through the sample and can feed the chamber with large amount of power without affecting the sample electrically. The second RF power source is a Bias power which located at substrate holder. This source is needed to form a plasma potential and obtain an anisotropic etch. Plasma density and ion energy play an important role in ICP etching process, they are control and determine by ICP power and Bias power respectively. In this way, the ICP system equipped with ICP power source and Bias power source which enable to create high density plasma and direct control the voltage at the sample surface.

Most significantly, the plasma is sustained without creating a high voltage sheath at the plasma-wall boundary. This improves the purity of the process and greatly increases the ion generation efficiency. The incident ion energy, which is induced by substrate bias, determine

vertical etch and the degree of channel. This is due to higher ion density produced at greater ICP power condition, which suppressed the self-biased power and ion energy. Since the ion energy reduced at higher ICP power region, less damage on the silica surface was obtained. Inductively coupled plasma (ICP) etcher is an important tool for semiconductor material processing, particularly to manufacture critical feature. The high plasma density enable ICP etcher produces high ion and radical densities and high etch rates capability.

Appendix 9: Plasma Generation and Characteristic

In general, plasma has three categories of plasma heating modes: capacitive (E), inductive (H), and helicon wave heated (W) modes, depending on the external parameters such as pressure, magnetic field, and RF power. The plasma impedances were determined by measurements of the amplitudes and phase shift of the current and voltage on the antenna which was considered as a primary coil. The plasma impedances determined by the electrical measurements were well defined and undergo a corresponding transition as the mode change of E-H-W. The transitions of the equivalent resistance and reactance were related as a function of rf power, pressure, and magnetic field.

In a plasma-etching environment, the anisotropy is provided by the acceleration of ions through the plasma sheaths in a direction normal to the wafer surface. The anisotropic component is maximized when the incoming ion flux is as normal as possible to the surface. The isotropic component of the incoming ion flux is either thermal (typically less than 0.1 eV, compared to several hundred eV for the sheath voltage), or caused by collisions of the ions in the sheaths with neutrals (either elastic or charge-exchange). Operation in a lower-pressure or higher-density regime provides much thinner and less collisional sheaths, making it possible to obtain a more anisotropic etching component [3]. The primary processing advantages of high-

density sources are better CD control, higher etching rates, selectivity, and an improved processing window.

The plasma is positively charged relative to the walls and wafer, and positive species known as ions are accelerated from the plasma in a direction normal to these surfaces. In contrast, electrons diffuse out of the plasma when the individual electron energy exceeds the plasma potential relative to the surface. Negative ions, at a much lower temperature and diffusivity, are generally unable to escape the plasma, being lost instead to recombination and detachment collisions. Thus, the ions travel to all of the horizontal surfaces, including those which are at the bottom of vias and trenches. If any portion of the etched structure and mask material is insulating, a voltage difference therefore builds up between the top surfaces of the mask and the bottom of the structures being etched. This voltage builds up until the electron and ion currents to the bottom of the structure are equal.

Thus, the low-energy ions are retarded, reflected, or reflected into the walls, while the electrons are pulled down into the structure. This causes features to charge top to bottom. As a result, ions are deflected to the sidewalls, causing notching [4]. Also, the reduced ion current [5] and energy of the ions that reach the bottom surfaces contribute an aspect-ratio-dependent phenomenon known as "RIE lag" [6], in which large features etch at a faster rate than small ones. The voltage build up causes threshold shifts [7], and the current flow through thin insulating layers can cause oxide and device damage. These effects have been shown to worsen as the aspect ratios of the IC structures increase [8, 9]. They can be lessened by reducing the electron temperature or reducing the ratio of electron temperature to the ion energy.

Some of these problems can be eliminated by using a hard mask for etching the silica core layer, thus reducing the aspect ratio of the etch result. Also, the etchant gas can be modified

to make the sidewall protection thicker and/or more durable. This is achieved by increasing the amount of etch gas and increasing the etching bias.

A number of researchers [7, 10] have shown that one solution is to pulse the plasma on and off with equivalent pulses with approximate 10 μ s in duration. During the off pulse, the electron temperature decreases to the order of 1 eV [11] through inelastic collisions and surface losses. Subsequently, the negative ion density increases relative to the electron density. This has been shown to reduce the notching effect [4]. The zero dc bias and low RF bias frequency allow the negative ions to be accelerated across the sheaths. The low RF bias frequency is needed to prevent the heating of the cooled electrons and thus take advantage of the low electron temperature during the off pulse.

The role of plasmas is to decompose stable molecules into chemically active species and to transport them onto surfaces on which various useful reactions take place. There, the main role of reaction is played by electrons the energy of which is one of key parameters to characterize reactive plasmas. Ion flux from plasma is a function of electron energy. Thus, control of electron energy is most important to control reaction in the reactive plasma for both fluxes of radical and ion.

A reactive plasma is described theoretically as a set of dynamic systems with both of the source and the loss term each of which is characterized with each own time constant evaluated with cross-section and basic parameters such as plasma dimension and gas pressure. The concept of time constants makes analysis of chemical reactions simple.

Ions and radicals in plasma play important roles in dry etching process. Positive ions are very important since they accelerated through the sheath. Other wise, negative ions play an important but secondary role since they don't reach the wafer under normal conditions. They can

influence plasma properties but rarely participate in the surface reactions of the etch process. When electronegative gases are used in plasma etching, the density of negative ions in the plasma can be higher than the electron density.

In processing plasmas, theoretically the ion to neutral fraction ranges from 10^{-2} for high density plasmas range from 10^{-4} to 10^{-6} for conventional RIE plasmas. Radicals are more abundant than ions in molecular gas glow discharges because they are generated at a higher rate than ions whereas lower threshold energy and ionization is often dissociative and they stay longer in the discharge than ions.

Appendix 10: Etch Profile / Profile Study

Several etch profiles are shown in figure 3, which are a) Anisotropic Etching (ideal sidewall passivation), b) Tapering (strong sidewall passivation), c) Bowing (ion trajectory distortion, mostly in dense areas), d) Undercutting (spontaneous etching), e) Notching (ion trajectory distortion and chemical etching).

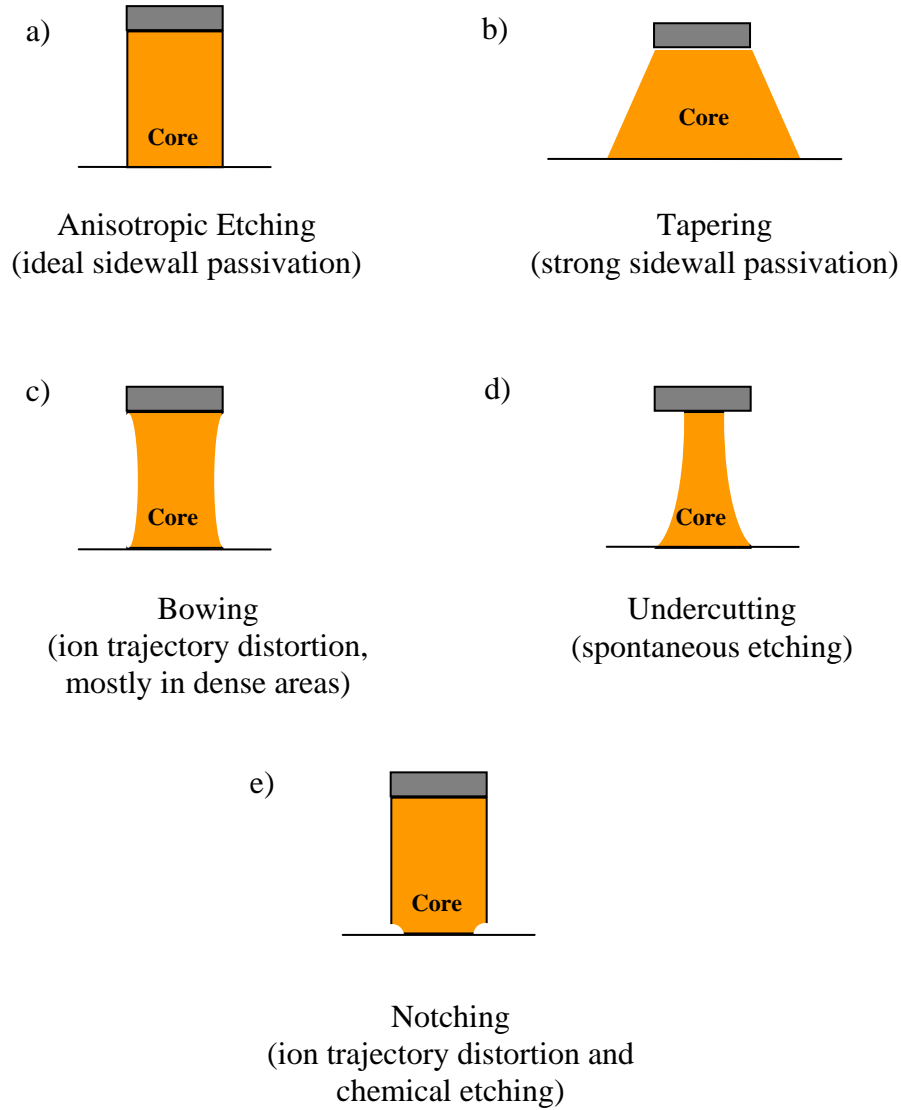


Figure 3: Several of dry etching profiles

Theoretically, ion and electron fluxes onto large open area are equal. Any vertical surface in the wafer or called feature sidewall screens a part of the flux and the flux of electrons arriving on the surface decreases. In contrast, the ion flux is not impacted. When the surface at the bottom is an insulator, it charges positively, possibly leading to a partial deviation of the ion flux. If the mask is an insulator, it will charge negatively. For two adjacent sidewalls either space between

two lines or trenches are present, the shadowing effect becomes even more pronounced. The insulator between the lines will be charged even more.

The very strong peak potential that develops close to the edge of the structure induces an ion trajectory distortion. Close to the edge of trenches, ions never reach SiO_2 at the bottom. They get deflected by the high potential at the bottom that develops on the SiO_2 surface and reach the sidewalls. There, the ions can generate some etching if their energy is high enough to punch through the passivation layer.

The term critical dimension (CD) control describes requirements and methods to transfer a critical dimension of a mask into the final dimension of the etched feature.

During etching, a sidewall passivation layer is formed. This layer with its finite thickness constitutes a deviation from the original mask dimension.

Critical dimension control is therefore sidewall passivation thickness control either dense or isolated lines across die, across wafer, and wafer-to-wafer. The thickness of the passivation layer in turn is controlled by the balance between etch and deposition within each etching step and for all steps in combination.

To achieve the highest possible pattern fidelity in advanced etches process, several hundred process parameters have to be selected and controlled in such a way that all features across a 4 inch wafer. In fact, anisotropy etch play an important roles in critical pattern transfer and is determined by the ratio of vertical etch rate to lateral etch rate where $A = 1 - E_{\text{horizontal}} / E_{\text{vertical}}$. For isotropic etching $A = 0$ and $A = 1$ when it was anisotropic etching. Secondly, selectivity comes to the aim of target etch depth that mask sufficiently compensate in etching process and is defined as the ratio of the etch rate of the etched layer to that of either the

underlying layer or the masking layer. Somehow, over-etching is needed to ensure the complete removal of the etched layer, necessitating the increased demand for higher etch selectivity.

Appendix 11: Etch Chemistry and Mechanism

Plasma etching process start with gas phase dissociation of input gases to become reactive species, and then adsorption of reactive species to the surface of material to be etches. Reaction of adsorbed species occurred with the exposed surface to form volatile product species and lastly, removal of reaction products and other residue species.

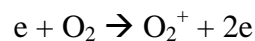
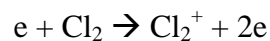
Several fluorocarbons etch gases such as CF_4 , C_2F_6 , C_4F_8 , SF_6 and CHF_3 are commonly used in semiconductor and photonics processing process. C_2F_6 is quite different from unsaturated fluorocarbons where it produces less $[\text{CF}]$ and $[\text{CF}_2]$ in constant carbon series, produces less $[\text{F}]$ in constant fluorine series. This fact comes to assumption that less efficient dissociation for C_2F_6 . Theoretically, dissociation of C_2F_6 has higher $[\text{CF}]/[\text{CF}_2]$ ratio and much higher $[\text{F}]/[\text{CF}_2]$ ratio which contribute less oligomerization and agrees with process knowledge that C_2F_6 is much less polymerizing than others fluorocarbon gases. Some classification of etch material, plasma chemistry and process parameters are shown in table 2.

Table 2: Classification of etch plasmas and process parameters

Material	Etch Chemistry	Reaction Product
Si	CF ₄ , SF ₆ , HBr, Cl ₂ , NF ₃ , HI	SiF ₄ , SiCl ₄ , SiF ₂ , SiCl ₄ , SiBr ₄ , SiI ₄
SiO ₂ , Si ₃ N ₄	CHF ₃ , C ₄ F ₈ , C ₂ F ₆ , SF ₆ , NF ₃	SiF ₄ , CO, CO ₂
Al	BCl ₃ , HCL, Cl ₂	Al ₂ Cl ₆ , AlCl ₃
W	SF ₆ , CF ₄ , NF ₃ , Cl ₂ , O ₂	WF ₆
Ti, TiN	Cl ₂ , O ₂	WOCl _x
Polymer	Cl ₂	TiCl ₄
InP,	O ₂ , O ₂ /CF ₄ , SO ₂	CO, H ₂ S, CO ₂ , HF, H ₂ , H ₂ O
HgCdTe	CH ₄ /H ₂	In(CH ₃) ₃ , PH ₃ , Cd(CH ₃) ₂
GaAs	Cl ₂ , BCl ₃	Ga ₂ Cl ₆ , AsCl ₃

Electron-Molecule collisions are the main channel for the creation of species that are used in plasma etching. Electron striking an atomic or molecular neutral can get attached and form a negative ion whereas a molecule with particularly large electron attachment cross section. Other wise, ionization caused by electron striking an atomic or molecular neutral to remove an electron and form a positive ion.

The reaction converts relatively inert molecules into very reactive radicals. The role of reactive radicals is very important in plasma etching where most of the plasma surface chemistry is achieved by radicals. The role of radicals depends also on the plasma density of the discharges whereas ions may be strongly involved in the chemistry in high density plasmas.



Dissociation and ionization may often simultaneously occur and the process is called dissociative ionization:





In general, dry etching mechanism consist of the process of plasma generation, etchant species generated in plasma, diffusion of etchant species to substrate surface, reactant absorption on the substrate surface, volatile compound form by chemical reaction along with ion bombardment, desorption and diffusion of etch product into bulk gas and lastly pump out by vacuum system. The etch mechanism flow is shown in figure 4.

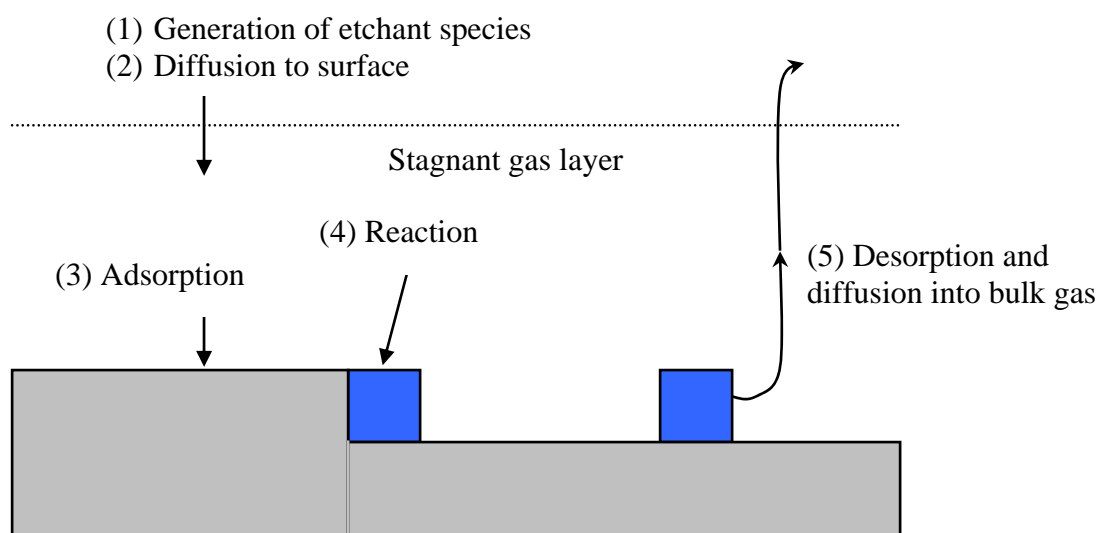


Figure 4: Etch mechanism of dry etching

Note that the desorption of the reaction by-products from the surface of the material being plasma etched is just as important as the occurrence of the chemical reactions that consume the material. If such desorption fails to occur, then etching can not take place even if the chemical reactions have been completed. Thus, all the steps above must occur for the plasma etching process to be successful.

Ion bombardments play an important role in plasma etching to provide directional etching. In plasma etching, Physical sputtering occurs when a surface is exposed to ion bombardment,

atoms and molecules can be ejected by energetic ions. Physical sputtering is a non selective phenomenon which the materials of different nature can be sputtered at similar rates. It is also a directional phenomenon which helps in obtaining anisotropic etching profiles.

Ion induced damage and surface adhesion whereas ion bombardment may favour neutral dissociation at the surface and increase the number of adsorption sites by generating some surface roughness and generating dangling bonds. Other wise, ion enhanced chemical reaction which ion bombardment may favour the desorption of etch by products.

On the other hand, chemical sputtering take part whereas ion bombardment may favour the desorption of etch by products. Ions act as a source of reactants that neutralized when reached the surface and become an additional source of reactive species. The illustration of ion bombardment chemical sputter etch is shown in figure 5. The role of ion bombardment in ICP RIE process, result anisotropy and enhanced ion bombardment etches where ion enhanced chemical sputtering reaction and reduced surface damage which improve etch selectivity.

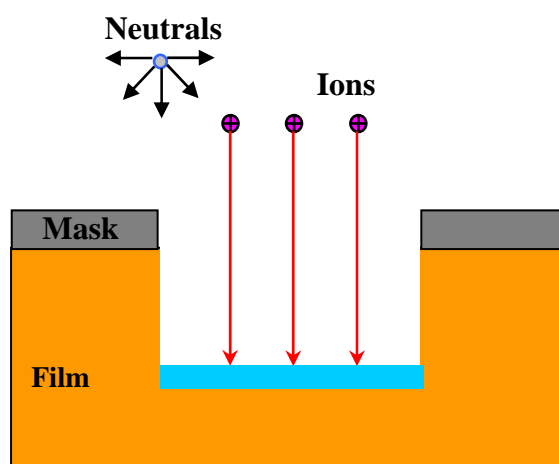


Figure 5: Ion bombardment chemical sputter etch

Generally, physical and chemical sputtering involved in by-product removal. Other wise, physical and chemical sputtering enhanced sidewall passivation formation due to back-sputtering of non volatile etch products as shown in figure 6.

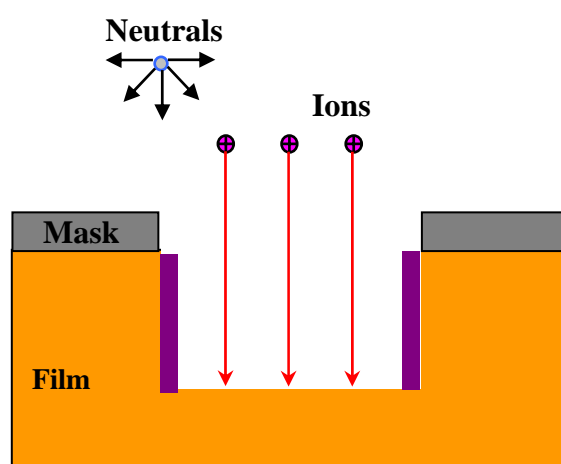


Figure 6: Sidewall passivation for physical and chemical sputtering

Ion bombardment plays an important role in dry etching process as factor influencing anisotropy. Ion energy flux primarily responsible for the etch anisotropy in plasma etching. In general, an increase in ion energy flux leads to a better anisotropy. On the other hand, the lower the neutral to ion flux ratio the better the anisotropy. Neutral species reactivity allows spontaneous reaction of neutral species to react with the surface. Reaction of neutral species with surface enable deposition of non-volatile etches products as forming a passivation layers at the feature sidewalls. In addition, substrate temperature would influences neutral species reactivity and reaction product deposition.

Plasma chemistry in polymer deposition is important and would have a different Aspect Ratio Dependent Etching (ARDE) behaviour than when there is pure chemistry. The relative of neutrals and ions are important in both etching and deposition and the transport of these into

features. Features with high aspect ratio (depth/width) have a higher etch rate than those with a small aspect ratio which known as normal ARDE. Under certain process conditions, the effect can be reversed which called reverse ARDE.

Inverse ARDE has been observed in high density plasma sources as well as ICP RIE type sources in SiO_2 etching using fluorocarbon based chemistries. When using polymerizing chemistries, polymer deposition can be more important in large open areas than in high respect ratio structures: the etch rate is therefore more important in high aspect ratio structures. Theoretical, feature dimension strongly influence the etch rate as typically large open areas etch faster than densely packed features.

In general, plasma etch mechanism consist of chemical etching, physical etching, ion enhanced etching, trenching, sidewall passivation, mask erosion and etc. The overall illustration of plasma etch mechanism is shown in figure 7.

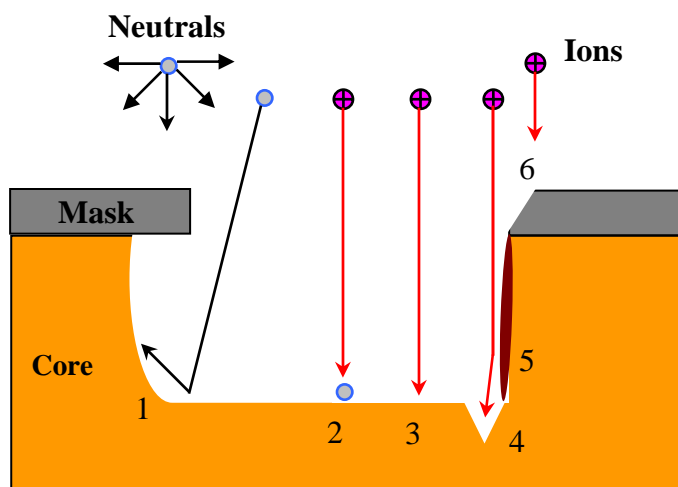


Figure 7: Mechanism of plasma etch

- | | |
|--------------------------|---|
| 1. Chemical etching: | Spontaneous, isotropic and very selective |
| 2. Ion enhanced etching: | Neutrals and ions involved, ion energy needed to stimulate chemical reaction or to remove reaction products |
| | Anisotropic and selective |

- | | |
|--------------------------|--|
| 3. Physical etching: | Anisotropic and non-selective |
| 4. Trenching: | Caused by ion deflection from sidewalls (surface scattering or influence of electric field of charged mask / sidewall) |
| 5. Sidewall passivation: | Deposition of non-volatile materials; etch by-products, surface reactions with certain feed gas additives, mask material |
| 6. Mask erosion: | Caused by ion bombardment / sputtering |

In macroscopic loading phenomenon, etch rate decreases when the total area of the material to be etched decreases and effects is caused by the consumption of reactive species produced by the plasma during the etching process as shown in figure 8. Macroscopic loading effect is most common for isotropic etches with spontaneous etch mechanism, for instance removal of poly-Si with SF_6 based plasmas. Certain poly gate over-etches also show significant macro-loading.

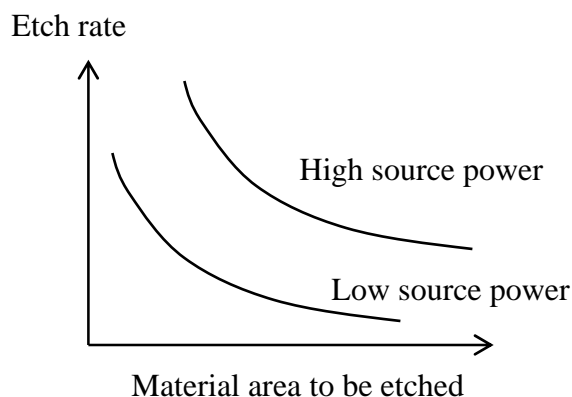
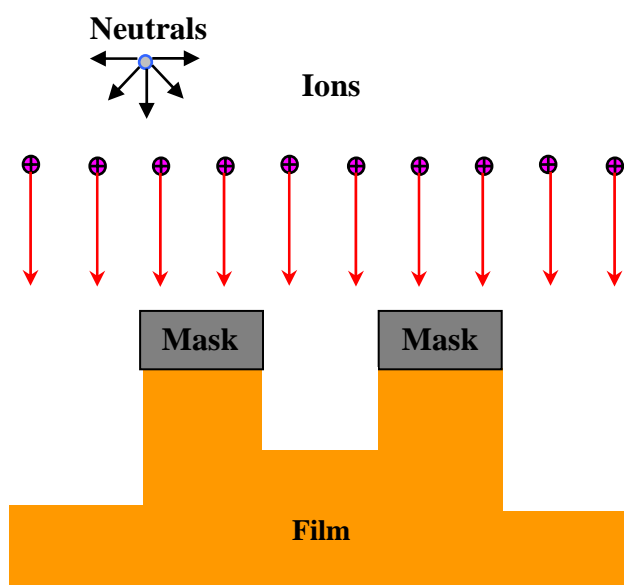


Figure 8: Etch rate over material area to be etched

Macro-loading is related to a change in plasma composition when wafers with different open areas are being etched, i.e. a change in the loading of the plasma with reactants and reaction products. Simply increasing the concentration of reactive species by increasing the source power is not practical because of the simultaneous product of reaction products.

Possible solutions such as dilution with inert gases and using higher pump speeds can result overall lower concentration of reaction products. Change of the process properties such that the limiting step is not the reactant supply for instance by adding passivating gases. In addition, to favour reactive species consumption or recombination on the chamber walls and plasma pulsing to allow reaction products to be removed

Microscopic loading effect involved where identical features are etches with different rates depending on their position with respect to open area features such as dense areas and semi dense areas as shown in figure 9. This effect is attributed to a localized depletion of etching species caused by the etching process itself. Etching process with strong macro-loading typically also exhibit significant micro-loading.



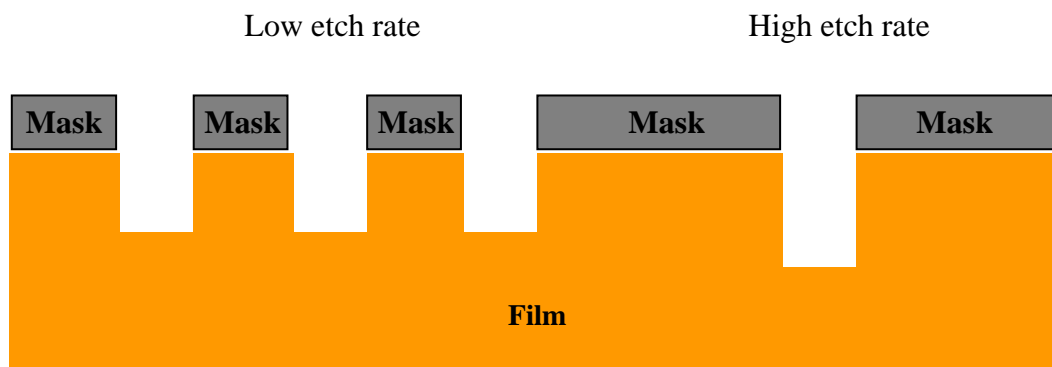


Figure 9: Different etch rate depending on density and feature of the etched area

Somehow in self clean chemistry concept, a high concentration of etch products are present in the gas phase: dissociation, re-deposition on the feature sidewalls and oxidation to form SiO_x on the sidewalls (1) and direct line of sight re-deposition from the bottom of the features is also possible (2) as shown in figure 10. Same mechanisms hold to explain the formation of SiO_x on the chamber walls and the chamber wall will be covered with SiO_x , SiF_x and others polymer deposit.

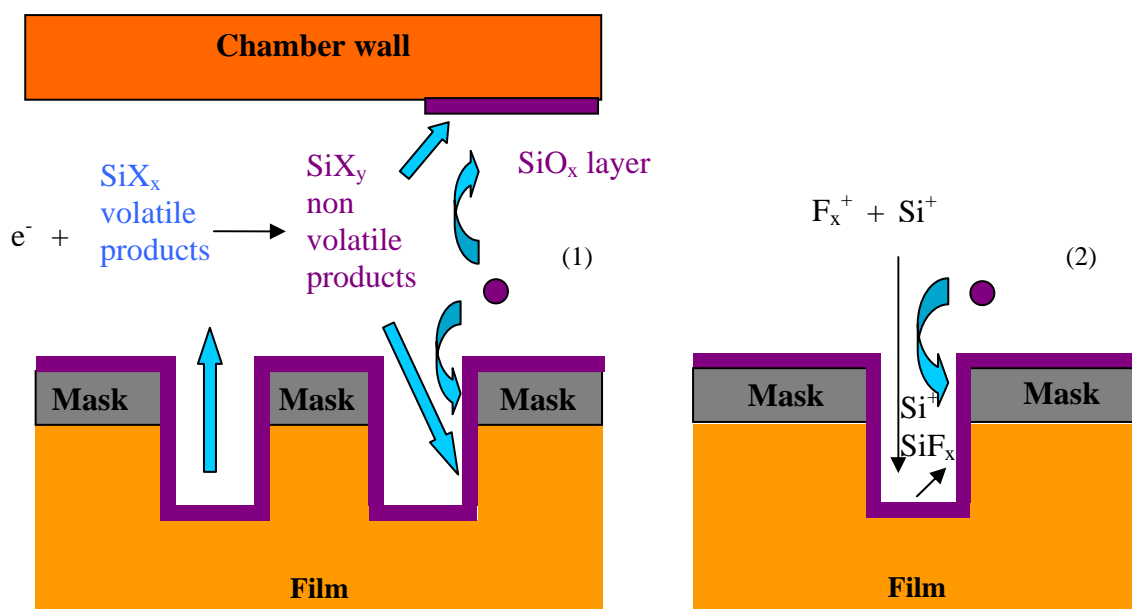


Figure 10: Etch mechanism of fluorine based etch gas

Other wise, self cleaning chemistry concept in CF_4 addition applied in cleaning the chamber wall of SiOx based passivation which the film is replaced by thin carbon rich layers as in Figure 11.

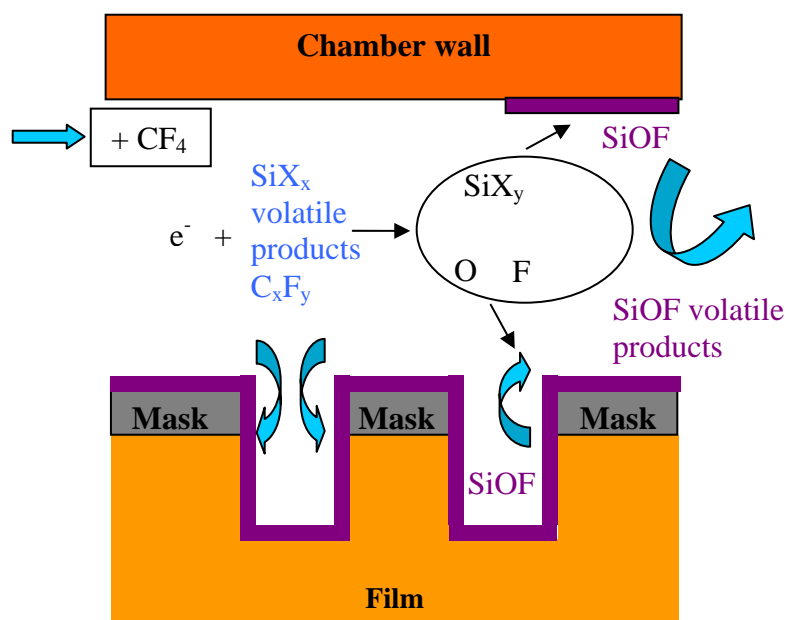


Figure 11: Self cleaning mechanism

Plasma Etching Mechanism

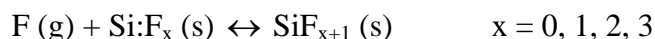
Anisotropic plasma etching has two components, chemical etching (neutrals and radicals of the plasma) and physical bombardment (ion assisted etching reactions). Very large scale integration (VLSI) plasma etch processes are characterized by a varying significance of the chemical and physical components. Chromium etching is a very chemical etch while SiO_2 etching has a very strong physical component. Silicon etch has strong chemical and physical components.

Commonly, reactive species would react chemically with surfaces and surface coverage is typically saturated at a few monolayer. Reactions are not very temperature sensitive because of low activation energies for the reactions. Condensable species normally form liquid or solid films

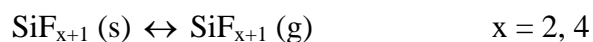
on surfaces and surface coverage depends strongly on the substrate temperature. For instance, polymer precursors (C_xF_y) are both condensable and reactive at room temperature. Somehow, neutral species that arrive at the wafer surface can stick to the surface and react. Depending on the sticking coefficients and reaction probabilities, reactive and condensable species can be distinguished among the species in the feed gas and the reaction products. The balance between reaction and condensation influences the etch profiles.

Spontaneous etching reactions in plasma etching known as chemical etching. Chemical or so-called “spontaneous” etching is the result of the interaction of reactive free radicals with the surface. Free radicals are electrically neutral species that have incomplete outer shells such as CF_3 and F . The mechanism of chemical etching consists of three elementary steps which are adsorption of reactive species on the surface and dissociation if it is a molecule; etch products formation by chemical reaction and etch products desorption. In a spontaneous etch process; these steps proceed without the need for activation by ion bombardment.

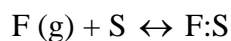
Physical and chemical surface processes are central to plasma processing. In F atom etching of silica, F atoms are created in the discharge, transported to the surface and fluorinate the surface through reaction such as:



Production of etch products transported back to gas phase as:

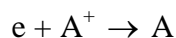


Adsorption and desorption reactions play a critical role in determining gas-phase species concentration such as:

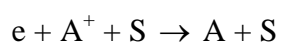


Discharge equilibrium affected by surface processes such as positive ion neutralization and secondary electron emission at surfaces.

Surface processes in positive ion neutralization, the strongly exothermic neutralization reaction is forbidden in the gas phase:



At the surface, the three body neutralization reaction is fast:



In processing discharges at ion energy range between 10-1000 eV, all positive ions are immediately neutralized at the surface. Heavy particles (ions and neutrals) have the same behaviour when they impact surfaces. At low thermal energies, physical and chemical adsorption and desorption can occur. In the tens of electron-volts energy range, molecules can fragment into atoms. Atoms can be sputtered from the surface in the thousands of electron-volts range and implantation happen in the hundreds of electron-volts range.

Surface processes such as adsorption and desorption are very important for plasma processing since one or the other of these reactions is the rate limiting step for a surface process. Adsorption ($A + S \rightarrow A:S$) is the reaction of a molecule with a surface and desorption is the reverse reaction.

Physical adsorption is the weak attractive van der Waals force between a molecule and a surface. Physical adsorption is exothermic with E_{physical} about 0.01-0.25 eV. Physically adsorbed molecules are so weakly bound to the surface that they can diffuse rapidly along the surface. Somehow, chemical adsorption is the formation of a chemical bond with the atom or molecule and the surface. The reaction is strongly exothermic with E_{chemical} about 0.4-4 eV. Chemical adsorption of a molecule having multiple bonds can occur with the breaking of one bond as the

molecule bonds to the surface ($A + B + S \rightarrow AB:S$). Molecules that are single bonded are often broken apart as they bond to the surface ($AB + S \rightarrow A:S + B:S$) two adsorption sites are required.

Surface processes also included fragmentation and sputtering. Fragmentation in the cases that ionic and neutral molecules with enough impact energy can fragment into atoms that are reflected or adsorbed when they hit a surface. Fragmentation happens when threshold in energy is of the order of the molecular bond where at energies four or five times above the threshold, 50% of the molecules fragment. In addition, high energy molecular ions with energy higher than 50 eV often fragment when they hit surfaces.

Somehow, large molecules show frequently delayed fragmentation. The kinetic energy of the impact is transferred into internal energy and redistributed among the bonds as vibrational and rotational energy. If this internal energy is higher than the bonding energy, the ion fragments along this bond. Large molecules with only type of atoms like C60 are especially resilient to collision induced fragmentation.

At energies above 20-30 V, heavy particles can sputter atoms from surface. The sputtering yield increases rapidly with energy up to a few hundred volts generating collision cascades in the solid bombardment. Above these energies, the yield is independent of the projectile energy and the target atom density.

$$\gamma_{sputter} = M_i / E_t (M_i + M_t)$$

where E_t is the surface binding energy, M_i and M_t are the incident ion and target atom masses.

At room temperature, anisotropy etch is always obtained from the formation of sidewall passivation layer. The sidewall passivation layer can be formed by different mechanisms such as mask etches products sputtered into the plasma gas phase by energetic ion bombardment and get

re-deposited on the feature sidewalls; condensable of some molecules or atoms originating from the dissociation of the feed gas stock; etch by products dissociation in the gas phase leading to the formation of partially volatile or non volatile etches by products which get re-deposited on the sidewalls and direct line of sight depositions of non volatile etch by products.

Theoretically, passivation comes from back-sputtering and gas phase re-deposition for traditional chemistry mechanism. In the illustration as shown in figure 12, re-deposition of resist etch products occurred on the channel sidewalls generating a carbon-based passivation layer. In the mean time, condensation of CF_x species from the fluorocarbon gas on the oxide sidewalls also contributes to the CF_y passivation layer formation. On the other hand, re-deposition of silica etch products from the plasma gas phase and direct line of sight deposition of silica etch products occurred due to sidewall passivation.

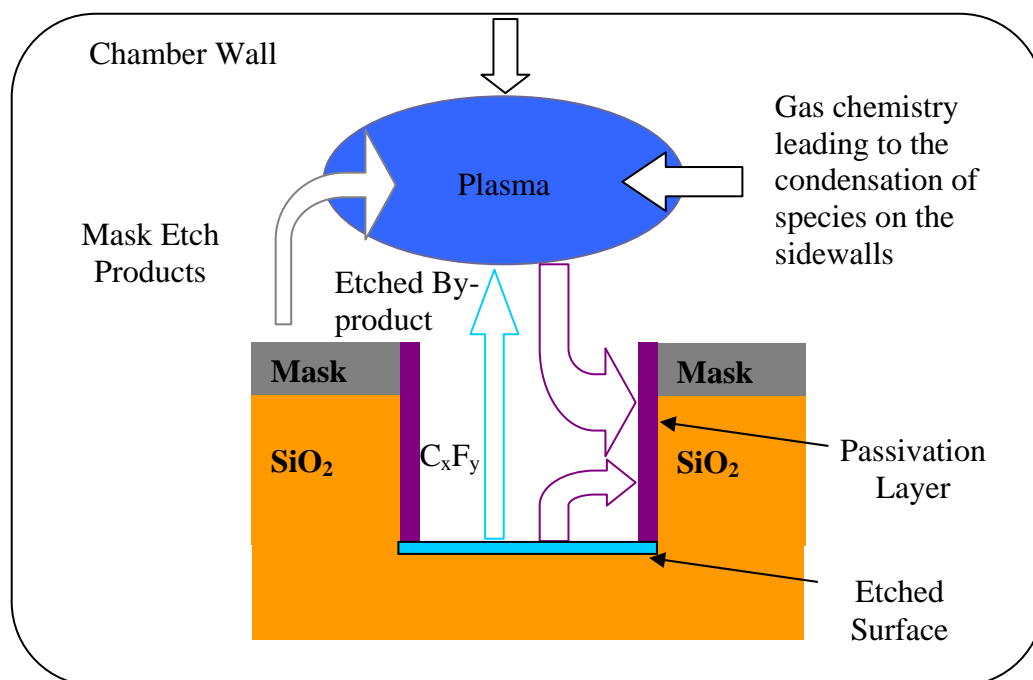


Figure 12: Mechanism of sidewall passivation

References

- [1] Katz, L. E., "Oxidation," in VLSI Technology, S. M. Sze (ed.), New York: McGraw-Hill, 1983, pp. 131–167.
 - [2] Williams, K. R., K. Gupta, and M. Wasilik, "Etch Rates for Micromachining Processing—Part II," *Journal of Microelectromechanical Systems*, Vol. 12, No. 6, December 2003, pp. 761–778.
 - [3] M. A. Lieberman and R. A. Gottscho, "Design of High Density Plasma Sources for Materials Processing," in *Physics of Thin Films*, M. Francombe and J. Vossen, Eds., Academic Press, Inc., New York, 1993.
 - [4] N. Fujiwara, S. Ogino, T. Maruyama, and M. Yoneda, *Plasma Sources Sci. Technol.* 5, No. 2, 126 (1996).
 - [5] K. Kurihara and M. Sekine, *Plasma Sources Sci. Technol.* 5, No. 2, 121 (1996).
 - [6] M. Sekine, H. Hayashi, H. Tamura, and K. Kurihara, Paper PS1-WeAl, presented at the 43rd National Symposium of the American Vacuum Society, Philadelphia, 1996.
 - [7] S. Samukawa and T. Mieno, *Plasma Sources Sci. Technol.* 5, No. 2, 132 (1996).
 - [8] N. Fujiwara, T. Maruyama, S. Ogino, and M. Yoneda, *Jpn. J. Phys.* 36, 2502 (1997).
 - [9] H. Arimoto, T. Kamata, and K. Hashimoto, *FUJITSU Sci. Tech. J.* 32, No. 1, 136 (1996).
 - [10] T. N. Ahn, K. Nakamura, and H. Sugai, *Plasma Sources Sci. Technol.* 5, No. 2, 139 (1996).
 - [11] J. Hahn, K. Chi, C. Jung, Y. Koh, and M. Y. Lee, *Jpn. J. Phys.* 36, 2450 (1997).
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